Impact Performance of 3D Printed Sandwich Structures: The Role of Core Geometry in Energy Absorption

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ABSTRACT

Impact Performance of 3D Printed Sandwich Structures: The Role of Core Geometry in Energy Absorption

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Innovative sandwich structures have gained prominence due to their potential to revolutionize industries with multifunctional performance. This study investigates the impact of different core topologies on the energy absorption capability of 3D-printed sandwich panels. Triply periodic minimal surfaces-based lattice structures and bioinspired spherical closed-cell foam structures were designed and compared against a traditional honeycomb structure to find the most suitable core topology. The fused deposition modeling technique was used to print samples in polylactic acid. The mechanical behavior of the 3D printing material was comprehensively characterized through a uniaxial tensile test. The sandwich panels were subjected to low-velocity impact loads to determine the dependence of their mechanical properties' responses on their topological features. Deformation mechanisms were investigated experimentally and numerically using ANSYS. The impact of cellular core topologies on deformation mechanisms, multi-hit (and impact location), and energy absorption capabilities demonstrated the possibility of enhancing mechanical performance of the panels. It is found that the sandwich panels with Tetra Radial and Schwarz P core topologies exhibit higher performance, denoted by higher dynamic energy absorption (up to 11% and 16%, respectively, for the 1st impact) and stiffness (up to 42%, and 43%, respectively, for the 1st impact) than the honeycomb structure (with a constant relative density). Significant enhancements in energy absorption, particularly in Schwarz P and Mono Radial panels compared to the previously reported Octet core structure, offer valuable insights for lightweight, durable 3D-printed sandwich structures, with broad applications in multifunctional industries and future trends in materials engineering, promising applications in aerospace, automotive, and construction for the development of weight-efficient, structurally robust materials.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 : INTRODUCTION

1.1 Background

The selection of suitable materials for addressing specific structural challenges necessitates a comprehensive assessment of multiple factors. These factors could include strength, stiffness, cost, durability, and both static and dynamic properties. Achieving the optimal balance between the weight and mechanical properties of the material is paramount to ensure the longevity and optimal performance of any structure. Otherwise, the material should be able to withstand the applied loads and environmental conditions without deforming or breaking. In today's engineering landscape, there is a growing demand for durable materials that can meet the ever-increasing challenges in various applications. These applications range from aerospace and automotive to biomedical and renewable energy. Therefore, in recent years, composite materials have received growing attention owing to their high performance, excellent mechanical properties, and ability to be customized for any application. Composite materials are made of two or more different materials that are combined to create a new material with enhanced properties [1], [2].

As illustrated in Figure 1.1, the demand for composite materials has witnessed substantial growth across a wide array of engineering fields, including aerospace [1], biomedical [3], defense [4], building and construction [5], and automobile components [6]. This surge in demand has spurred the development of advanced composite materials. One noteworthy area where composite materials are in high demand is the aerospace industry, driven by the imperative to reduce the weight of aerospace components [7]. Composite structures offer a range of exceptional features when compared to traditional metal counterparts. These advantages include enhanced bending stiffness, superior dimensional stability, low thermal conductivity, and effective acoustic insulation [8]. These attributes collectively contribute to the creation of efficient lightweight structures characterized by high specific bending strengths and stiffness [2].

A particularly compelling aspect of composite materials in structural design is the emergence of lightweight sandwich panels that have garnered increasing popularity due to their unique mechanical properties, which include lower density, a higher stiffness-to-weight ratio, a superior strength-to-weight ratio, and well-defined energy absorption properties [9], [10].

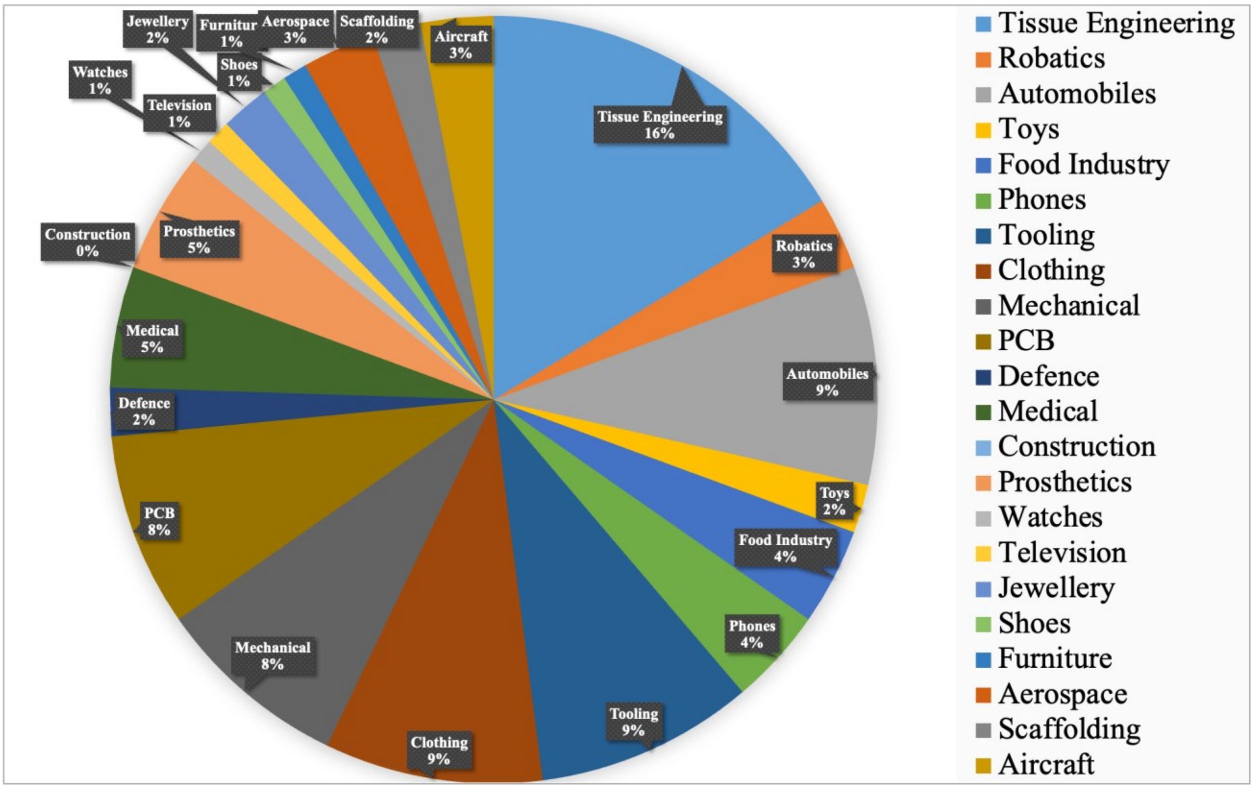

Figure 1.1. Percentage of using 3D printing in various industry applications [7].

Sandwich structures are composed of two thin face sheets bonded to a thick core, which can be either solid or cellular. The mechanical properties of sandwich structures depend on various factors including materials, geometry, and core topology. The core topology refers to the arrangement and shape of the cells that form the core [10]. To develop and enhance cellular structures for purposes, such as energy absorption, thermal insulation, and impact resistance, it is crucial to understand the mechanical behavior of cellular materials. Cellular materials exhibit different responses under different loading conditions, such as compression, tension, bending, and shear [11]. Therefore, studying cellular core topology's effects on the optimization of sandwich structure performance is crucial for advancing their multifunctional capabilities in various applications. These applications include aerospace, automotive, marine, civil engineering, and biomedical engineering. As illustrated in Figure 1.2, cellular materials can be classified as either stochastic (foams) or periodic unit cells, with open or closed-cell morphology. Stochastic foams have irregular and random cell shapes and sizes, while periodic unit cells have regular and uniform cell shapes and sizes. Open-cell foams have interconnected pores that allow fluid flow, while closed-cell foams have isolated pores that prevent fluid flow. The choice of cellular material depends on the desired properties and functions of the sandwich structure. The mechanical properties of sandwich structures depend on various factors including materials, geometry, and core topology [12], [13].

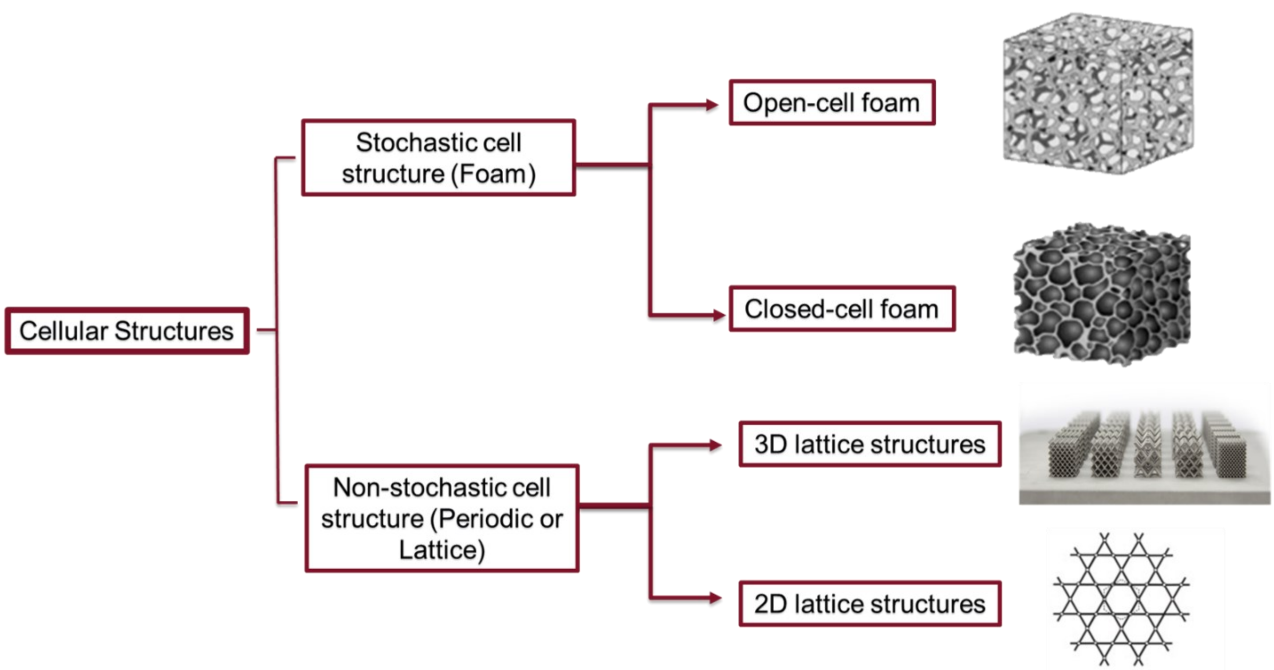

Figure 1.2. Categories of cellular structures.

To develop and enhance cellular structures for purposes, such as energy absorption, thermal insulation, and impact resistance, it is crucial to understand the mechanical behavior of cellular materials [14]. Therefore, studying cellular core topology's effects on the optimization of sandwich structure performance is crucial for advancing their multifunctional capabilities in various applications [15]. As illustrated in Figure 1.2, cellular materials can be classified as either stochastic (foams) or periodic unit cells, with open or closed-cell morphology [16]. Throughout the operational lifespan of aircraft sandwich components, impacts are anticipated to occur due to various factors. These may encompass typical in-service events such as high-velocity debris incidents during aircraft takeoffs and landings, or collisions with avian wildlife. Additionally, impacts may result from tool-related incidents, either during the manufacturing process or maintenance activities. Such damage can lead to the deterioration of structural stiffness and strength, potentially progressing further under subsequent loading conditions. Furthermore, the relatively limited resistance of sandwich structures to localized impacts has engendered concern within the aerospace industry [17].

Additionally, the integration of sandwich panels in structural engineering is a testament to the continuous evolution of materials science and engineering practices. Experimental and numerical modeling can be effectively utilized to predict the response behavior of sandwich panels for design and manufacturing purposes subjected to impact tests. Experimental modeling involves conducting impact tests on sandwich panels using different equipment and techniques, such as drop-weight towers, gas guns, or pendulums. Numerical modeling involves simulating the impact tests using different software and tools, such as finite element analysis (FEA), discrete element method (DEM), or smoothed particle hydrodynamics (SPH) [18]. These methods can provide valuable information about the impact response of sandwich panels, such as the deformation, stress, strain, energy absorption, damage initiation, and damage propagation [19].

Recent advancements in additive manufacturing (AM), also known as 3D printing, have opened new possibilities to produce sandwich panels with improved performance and functionality AM allows the fabrication of intricate parts using various materials, such as metals, ceramics, polymers, and composites. These materials can be combined or arranged in different ways to create novel structures with desired properties and characteristics. One of the applications of AM in sandwich structures is the fabrication of architected cellular cores with complex, free-form topologies in both 2D and 3D configurations. These cores can have different shapes and patterns, such as honeycombs, lattices, trusses, or auxetics. These cores can offer advantages over conventional cores made by extrusion, expansion, or corrugation methods, such as higher stiffness-to-weight ratio, higher strength-to-weight ratio, higher energy absorption capacity, higher thermal conductivity, higher acoustic insulation, or tunable mechanical behavior [20], [21].

1.2 Aims and Objectives

The primary objective of this study is to investigate how the impact response and damage of sandwich panels are influenced by various core topologies, and to determine the optimal core topology that can maximize the energy absorption capacity of sandwich panels. To accomplish this objective, a comprehensive analysis was conducted using a combination of experimental tests and numerical modeling. Experimental tests involved subjecting sandwich panels with different core topologies to low-velocity impact tests using a drop-weight tower. Sensors attached to the weight and the specimen measured the impact load and deformation of the specimen. These experimental tests provided valuable data regarding the impact response and damage incurred by sandwich panels with varying core topologies.

The numerical modeling, employing a finite element model, replicated the low-velocity impact tests performed on the sandwich panels with different core topologies. It applied identical boundary conditions and loading conditions as those used in the experimental tests. The finite element model predicted the impact response and damage of sandwich panels with different core topologies, encompassing variables such as deformation, stress, strain, energy absorption, damage initiation, and damage propagation. The synergy between experimental tests and numerical modeling offered a comprehensive understanding of how diverse core topologies influence the impact response and damage of sandwich panels. Verification of the accuracy and reliability of the numerical model was achieved through comparison with the results obtained from the experimental tests. The numerical model provided a more detailed insight into the impact response and damage of sandwich panels with different core topologies by elucidating the distribution and evolution of various variables throughout the structure.

A novel aspect of this study is its focus on plastic deformation and its relationship with energy absorption in sandwich panels with various core topologies under low-velocity impact loading. Prior studies have primarily concentrated on the analysis of elastic properties and unit cell responses, often simplifying or neglecting plastic deformation and its influence on energy absorption. However, plastic deformation significantly affects the energy absorption capacity of sandwich panels under low-velocity impact loading, allowing for greater dissipation of impact energy through permanent deformation. Hence, this study investigates the occurrence of plastic deformation and its effects on energy absorption in sandwich panels with diverse core topologies under low-velocity impact loading.

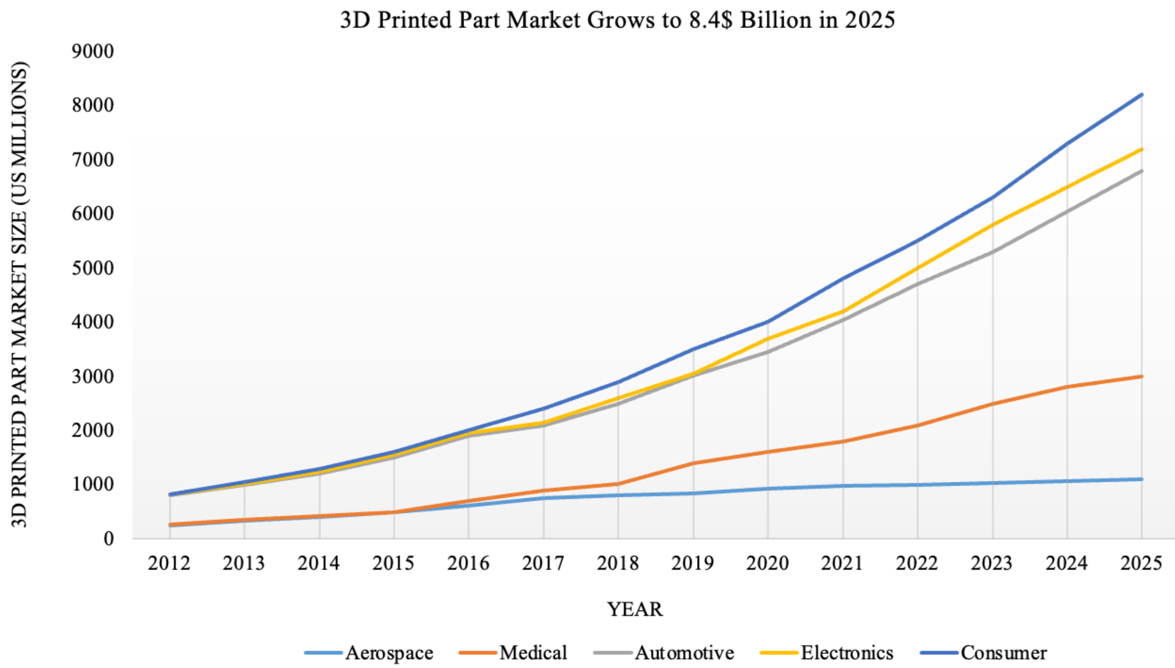

Figure 1.3. 3D printed growing market 2012 to 2025 [69]

Another novel aspect of this study is the consideration of not only the energy absorption capacity but also the failure mechanisms and multi-hit capability of sandwich panels with various core topologies under low-velocity impact loading. Failure mechanisms encompass the initiation and propagation of damage in sandwich panels during low-velocity impact loading, including delamination, core crushing, face sheet debonding, or perforation. These failure mechanisms influence not only the energy absorption capacity but also the residual strength and stiffness of sandwich panels after impact loading. The multi-hit capability assesses how well sandwich panels can withstand multiple impacts without compromising their functionality or integrity. This aspect is especially pertinent to applications where sandwich panels may experience repeated impacts during their service life, such as in military or aerospace vehicles. Therefore, this study analyzes the variations in failure mechanisms and multi-hit capability among sandwich panels with different core topologies under low-velocity impact loading.

The goal of this study is to design optimized sandwich structures with enhanced energy absorption capabilities under low-velocity impact loading by exploring various core topologies. This objective aligns with the broader aim of enhancing the performance and reliability of sandwich structures in structural engineering applications and contributing to the advancement of materials science and engineering practices.

1.3 Thesis Outline

Comprising a comprehensive thesis centered on the Impact Performance of 3D Printed Sandwich Structures: The Role of Core Geometry in Energy Absorption, this study is structured into six distinct chapters, each defining a particular aspect of the research. The outline for each chapter is presented below:

Chapter 1: Introduction

Chapter 1 serves as the foundational cornerstone of this research, illuminating the context and significance of the study. In this narrative, a journey unfolds into the realm of composite materials and their diverse applications, particularly within the aerospace sector. The narrative places deliberate focus on the significance of manufacturing methods in shaping these advanced materials. Additionally, it explores the essential role of modeling in comprehending defects and irregularities within composite structures, unraveling the complex interplay between material characteristics and manufacturing processes. The introduction culminates with a clear articulation of the study's aim and objective, providing a roadmap for the chapters that ensue. In the upcoming sections, traversal through a landscape of experimental investigations is undertaken, employing rigorous testing and finite element analysis to unlock the secrets of mechanical properties. This pursuit is not only academically intriguing but, more importantly, contributes invaluable insights for enhancing composite manufacturing practices and elevating the performance of composite materials.

Chapter 2: Literature Review

Chapter 2 serves as an extensive review of relevant literature in the field of composite materials, with a particular focus on sandwich panels. This chapter delves into the various categories and properties of composite materials, elucidating the factors that exert influence on the mechanical behavior of these panels. Additionally, it briefly touches upon the manufacturing technologies relevant to the fabrication of sandwich panels and covers topics concerning low-velocity impact testing and energy absorption capacity.

Chapter 3: Materials and Methods

- Core Design: The chapter kicks off with a comprehensive examination of the core design. The core is a fundamental component of sandwich panels, and its design can significantly influence the mechanical properties and overall performance of these panels. The section takes readers through the intricacies of selecting the core topology, which serves as the structural foundation for the sandwich panels. Core topology choices may range from traditional honeycomb structures to more innovative designs such as Triply Periodic Minimal Surfaces (TPMS) based lattice structures and bioinspired spherical closed-cell foam structures. This is where the architecture of your sandwich panels comes to life.
- Sample Preparation: To execute accurate and insightful experiments, the section on sample preparation is critical. It details how the sandwich panel samples were meticulously prepared for various tests. This includes specifics on the size, shape, and configuration of the samples, as well as the necessary steps to ensure their uniformity. Proper sample preparation is vital for achieving reliable and repeatable experimental results, and this section outlines the steps taken to ensure the samples meet these criteria.
- Material Properties Analysis: A significant portion of this chapter is devoted to the comprehensive analysis of material properties. This is where the heart of understanding the mechanical behavior of your materials lies. The analysis spans a range of key properties, from tensile strength and stiffness to energy absorption and deformation characteristics. The section discusses the methods employed to characterize these properties, which may include tensile testing, impact testing, and possibly more specialized tests suited to your materials. The results of these analyses serve as the foundation for your research and subsequent comparisons between various core topologies.
- Procedures for Low-Velocity Impact Tests: This section goes into the nitty-gritty details of how the low-velocity impact tests were conducted. It explains the experimental setup, including the equipment used, the positioning of sensors, and the specifications for the

impactor. It outlines the sequence of events during the tests, providing an understanding of how data was collected, including information on the impact load and deformation. These details are essential for readers to grasp the experimental conditions and ensure the reliability of the results obtained.

- Numerical Modeling Techniques: The last part of this chapter delves into the realm of numerical modeling techniques. In this section, the methods utilized for simulating the behavior of sandwich panels through finite element analysis (FEA) are discussed. Furthermore, the simulation may elaborate on the selection of software, the modeling approach, the boundary conditions, and other specifics that were integral to achieving accurate numerical predictions. The discussion of numerical modeling techniques helps align the experimental findings with the theoretical expectations and contributes to a deeper understanding of the mechanical properties of the materials.

In summary, Chapter 3 serves as the practical foundation of your research. It begins with the design of the core topologies, progressing to the preparation of samples, a comprehensive analysis of material properties, details on the execution of low-velocity impact tests, and a thorough exploration of numerical modeling techniques. Each section plays a crucial role in providing the necessary tools, data, and methodologies for the subsequent chapters, which investigate the mechanical behavior of your sandwich panels.

Chapter 4: Experimental Validation and Core Topology Analysis

- Experimental Validation: This segment of Chapter 4 serves as the bridge between theory and practice. It is here that the results obtained from your low-velocity impact tests in Chapter 3 are put to the test. Experimental validation refers to the process of comparing the real-world results you obtained during your tests with the theoretical predictions or numerical models developed in Chapter 3. The chapter outlines how this validation was performed, providing insight into the equipment, test conditions, and data collection methods used to ensure the reliability and accuracy of your experimental findings. This section might discuss any variations, discrepancies, or correlations discovered between the experimental data and numerical predictions, offering a critical evaluation of your research.

- Core Topology Analysis: The section discusses the analytical aspects of your research, delving into how the various core topologies were assessed. It explains the criteria used to evaluate their performance, such as load-carrying capacity, stiffness, and, importantly, energy absorption. In this section, the quantitative and qualitative findings are presented, outlining the outperformance of specific core topologies and potentially emphasizing trends and comparisons between them. A closer examination of the practical implications of the research is facilitated, laying the foundation for subsequent conclusions and recommendations.

Chapter 5: Conclusions, Contributions, and Future Works

Chapter 5 marks the point of this extensive research journey. It functions as a comprehensive summation, drawing together the multifaceted elements explored in this study. In this section, the core findings, experimental results, and analytical insights that have emerged throughout the research process are revisited. A holistic perspective on the outcomes of the study is provided, allowing a cohesive summary of the main findings. The value and implications of the research in the context of sandwich panels, core topologies, and the probed mechanical behaviors are emphasized. This summation is not merely a repetition but a strategic reminder of the core contributions of the research.

Beyond summarizing the findings, this chapter adopts a reflective tone, delving into how the discoveries can be translated into practical applications and their role in advancing the field of materials science. Furthermore, the horizons of future research and innovation are explored, aiming to inspire continued exploration in this domain. The reflective conclusion is a moment to underscore the depth of understanding and the intellectual growth achieved throughout this research journey. It resonates with the broader context in which the study is situated, leaving readers with a sense of the lasting impact of the work and the promise of future research.

Chapter 6: References

Chapter 8 serves as the reference section, where all the sources, studies, and literature cited throughout the thesis are meticulously documented, ensuring the work's academic integrity, and providing readers with the opportunity to delve deeper into the referenced materials.

CHAPTER 2 : LITERATURE REVIEW

2.1 Sandwich structures

A composite material is defined as a combination of two or more constituents. Typically, the attributes of these components are amalgamated to achieve specific properties that cannot be attained by individual constituents alone. In this study, the sandwich panels were investigated which represent a distinct subset of composite materials. These properties may include high strength, low weight, high stiffness, high toughness, high thermal conductivity, or high electrical conductivity. Composite materials are widely used in various fields, such as aerospace, automotive, construction, and biomedical engineering [13].

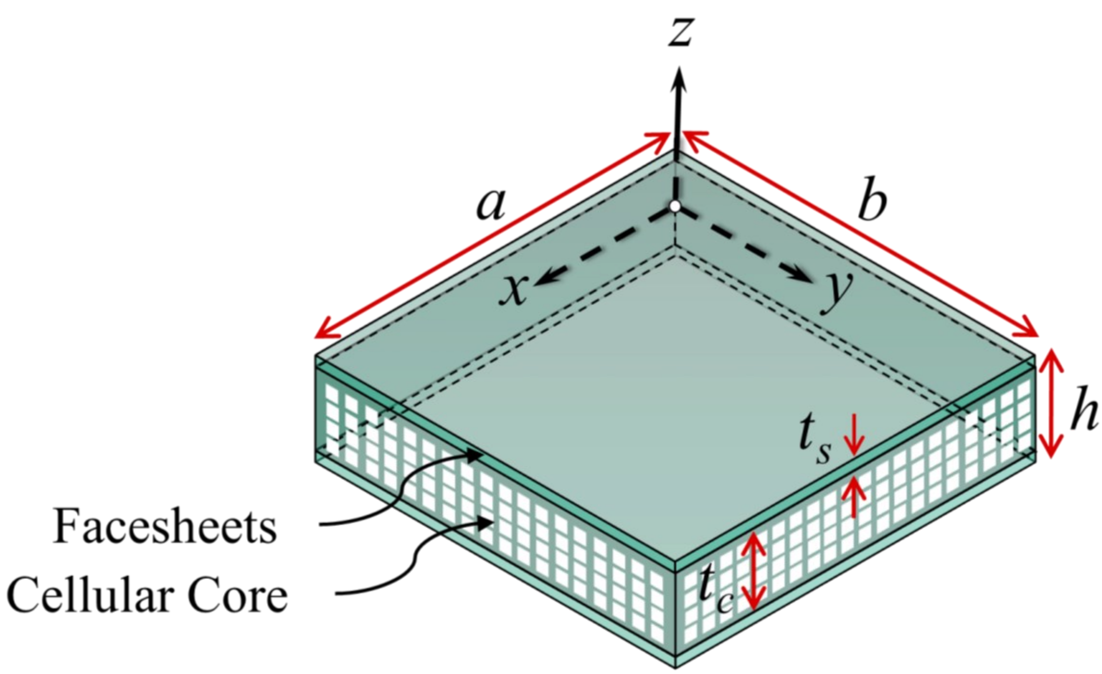

Figure 2.1. Geometry of an architected sandwich panel.

In this study, the sandwich panels were investigated which represent a distinct subset of composite materials. Standard sandwich structures comprise a lightweight core material positioned between two thin face sheets or skins. The core material provides thickness and stiffness to the sandwich panel, while the face sheets provide strength and resistance to bending. The core and face sheets can be made from different materials, depending on the desired performance and application of the sandwich panel [20]. Three common types of core materials are balsa wood, honeycomb structures, and rigid foams. Balsa wood is a natural material that has a low density and high compressive strength. Honeycomb structures are artificial materials that have a cellular geometry and a high strength-to-weight ratio. Rigid foams are synthetic materials that have a closed-cell structure and a low thermal conductivity. Typically, face sheets are made from materials such as aluminum, fiberglass, graphite, and aramid. These materials have high tensile strength and modulus and can be bonded to the core material using adhesives or mechanical fasteners [22].

The advantage of this sandwich construction lies in placing the rigid face sheets at a greater distance from the neutral axis during bending, akin to the flanges of an I-beam. Nevertheless, it is crucial to emphasize that the design of both the core and face sheets must be approached as a unified composite structure. Notably, the influence of the cellular structure of sandwich panels on enhancing the mechanical properties of these panels could be mentioned as the significant importance [23]. The increasing popularity of sandwich panels in various applications is attributed to their exceptional properties, characterized by their remarkable lightweight nature coupled with exceptional strength and stiffness. This results in an outstanding strength-to-weight ratio [9]. Despite this, the main weakness of such structures has always been the poor rigidity in the transverse direction. Impact dynamics analysis is carried out to predict the structure's impact response [24]. Impact dynamics analysis is a method of studying how a structure behaves when subjected to a sudden or dynamic load, such as a collision, blast, or drop. It involves modeling the material behavior, deformation, damage, and failure of the structure under different impact scenarios [25].

The mechanical properties of sandwich panels can be significantly influenced by various factors, encompassing relative density, expansion ratio, core geometries, the manufacturing process, and the choice of materials. These factors collectively play a substantial role in shaping the performance characteristics of sandwich panels [25]. Relative density is the ratio of the density of the core material to the density of the solid material. Expansion ratio is the ratio of the volume of the core material to the volume of the solid material. Core geometries include parameters such as cell size, shape, orientation, and arrangement. The manufacturing process involves techniques such as 3D printing, injection molding, extrusion, and casting. The choice of materials includes selecting suitable materials for the core and face sheets based on their mechanical, thermal, electrical, and chemical properties [26].

2.2 Additive Manufacturing (AM) Technologies

Recent advancements in additive manufacturing (AM) technologies have ushered in the ability to produce intricately designed cellular cores with free-form topologies, available in both two-dimensional (2D) and three-dimensional (3D) configurations. These cellular structures exhibit highly complex geometries that were traditionally challenging to achieve through conventional manufacturing methods used to produce sandwich structures, such as extrusion, expansion, and groove [21].

Additive manufacturing (AM) is a revolutionary process that differs from traditional subtractive manufacturing. Instead of removing material from a block, it involves constructing an object by adding layers of material based on 3D model data. AM represents a powerful transformation in the manufacturing industry, providing a novel approach to crafting intricate geometries with unparalleled precision and accuracy [27]. Additionally, the layer-by-layer approach intrinsic to AM is especially advantageous for creating components with intricate internal features, as seen in the architected cellular cores used in sandwich structures [28]. Over recent years, there has been significant progress in Additive Manufacturing (AM) which has enabled the production of intricate and complex parts using various materials such as metals, ceramics, polymers, and composites. This technological advancement has positioned AM as one of the most promising and innovative technologies of the near future [26], [29].

The adoption of AM in manufacturing processes offers a multitude of benefits, including a reduction in material waste, shorter production cycles, and decreased production costs [30]. 3D printing, a subset of AM, has attracted substantial interest due to its simplicity in manufacturing, the capacity to create intricate parts, a growing variety of printable materials, the ability to fabricate multi-material objects, the customization of microstructures, and decreasing associated costs. Owing to these advantages, 3D printing has found applications in the creation of various functional devices, ranging from energy storage devices (e.g., lithium-ion batteries, super-capacitors, and fuel cells) [31], [32], electronic devices [33], biomedical devices [34], and a range of sensors [35]. However, it's important to note that the reliability of 3D printed components is an ongoing area of investigation, as the 3D printing process can introduce manufacturing defects that need to be addressed [36].

Material extrusion-based 3D printing technology empowers the creation of multi-material and multi-color prints, making it renowned for its widespread adoption and cost-effectiveness. Furthermore, this method enables the fabrication of fully functional components seamlessly integrated into the product. One of the pioneering examples of material extrusion systems is Fused Deposition Modeling (FDM). The FDM process constructs parts incrementally, layer by layer, starting from the base and progressing upward. This is achieved by heating and extruding thermoplastic filament. The operational sequence of FDM is as follows: The thermoplastic material undergoes heating until it reaches a semi-liquid state, and it is then meticulously deposited in minute beads along the designated extrusion path. In situations necessitating support or buffering, the 3D printer deposits a removable material to serve as scaffolding [37].

2.3 Effective parameters on the mechanical behavior of sandwich panels

The mechanical characteristics of a sandwich structure are the result of a complex interplay among several critical factors, each contributing uniquely to the structure's overall performance. The mechanical behavior, energy dissipation ability, and failure mechanism of a cellular sandwich structure are affected by various factors including constituent material, geometrical parameters, and core cell topology [38]. Constituent material refers to the type and properties of the material used for the core and face sheets of the sandwich structure. The material selection depends on the desired performance and application of the sandwich structure, such as its strength, stiffness, weight, durability, and cost. Some common materials used for sandwich structures are metals, ceramics, polymers, and composites [39].

Geometrical parameters refer to the dimensions and proportions of the core and face sheets of the sandwich structure, such as their thickness, length, width, and area. The geometrical parameters affect the mechanical properties and performance of the sandwich structure, such as its bending stiffness, buckling resistance, and deformation mode. Core cell topology refers to the shape and arrangement of the core cells within the sandwich structure, such as their geometry, size, density, and orientation. The core cell topology influences the stress distribution, energy absorption, and failure mechanism of the sandwich structure, such as its peak stress, specific energy absorption, and fracture pattern [21].

Recent studies have highlighted the significant impact of cellular core geometry on the multifunctional performance of sandwich structures [2], [14]. Therefore, the foremost factor to highlight is the geometric arrangement of the sandwich structure, which involves precisely defining the dimensions, proportions, and layout of components like the core, face sheets, and other structural elements. The geometric design profoundly influences key mechanical properties, including load-bearing capacity, resistance to bending, and deformation resilience [12]. Through the optimization of geometric design, the efficiency and effectiveness of the structure in supporting intended loads and responding to external forces can be significantly enhanced [15]. Moreover, the role of core topology is of paramount importance in molding the mechanical behavior of the sandwich structure. Core topology pertains to the specific arrangement and configuration of the core material within the sandwich. This factor considerably shapes stress distribution, energy absorption during impact incidents, and overall structural integrity. Whether a honeycomb, foam, or lattice core is utilized, each topology presents distinctive advantages and constraints, necessitating careful consideration according to the intended application and performance requisites [13]. By optimizing the microstructure of the cellular core, encompassing its form, dimensions, and distribution, the mechanical performance and energy absorption attributes of the sandwich structure can be enhanced [40].

2.4 Energy absorption capability of sandwich panels

To develop and enhance cellular structures for purposes, such as energy absorption, thermal insulation, and impact resistance, it is crucial to understand the mechanical behavior of cellular materials. The structural performance and the crucial capacity for energy absorption within an architected sandwich panel are inherently reliant upon a delicate interplay of material properties and geometric attributes found in both the solid face sheet and the cellular core [41]. Based on their structure, cellular materials can be classified as either stochastic (foams) or periodic unit cells, with open or closed-cell morphology [16]. The comparative behavior of closed-, partially closed- and open-cell structures were investigated, and reported that removing cell walls from a closed cell to make a partially open structure degrades their mechanical properties including lower stiffness-to-weight ratio, and the lower strength-to-weight ratio [42]. The topology of the unit cell and its relative density, which is calculated as the density of the cellular material divided by the density of its constituent materials, are two factors that affect the physical properties of cellular materials and have a major impact on their mechanical properties [43].

Among the diverse cellular core configurations meticulously explored for architected sandwich panels, the hexagonal honeycomb structure has consistently taken center stage as a prominent and extensively studied choice [44]. In practical terms, the exceptional energy absorption capabilities exhibited by sandwich panels featuring the hexagonal honeycomb cellular core render them invaluable in applications where impact resistance and shockwave attenuation are of paramount importance. Industries such as sports equipment, automotive manufacturing, and aerospace engineering have long recognized the remarkable benefits of these panels [45], [46]. However, they have some issues due to their closed-cell architectures including gas retention, leading to low thermal conductivity and moisture trapping. Moisture trapped in the closed-cell cores increases the weight and shifts the center of gravity, a problem that can be resolved by using open-cell cores [1]. However, it is essential to acknowledge that despite their considerable advantages, conventional honeycomb cellular cores present challenges attributed to their cell architecture. Issues such as gas retention within these closed cells have been identified, leading to a decrease in thermal conductivity and moisture entrapment. The accumulation of moisture within these closed-cell cores not only contributes to increased weight but also induces a perceptible shift in the center of gravity, potentially compromising the panel's overall performance [1].

2.5 Influence of core geometry on the sandwich panels' mechanical behavior

Cellular materials can be categorized based on their structure into two primary classes: stochastic, exemplified by foams, and periodic unit cells, characterized by open or closed-cell morphologies [16]. A comparative analysis was conducted to explore the performance distinctions among closed-cell, partially closed-cell, and open-cell structures. The findings revealed that the removal of cell walls from a closed cell to create a partially open structure detrimentally affects their mechanical attributes, resulting in a reduced stiffness-to-weight ratio and diminished strength-to-weight ratio. The unit cell's topology and its relative density, which is calculated as the density of the cellular material divided by the density of its constituent materials, are two factors that affect the physical properties of cellular materials and have a major impact on their mechanical properties [42]. Recent times have witnessed a notable upsurge in interest surrounding an innovative class of closed cellular structures referred to as plate-type structures and Triply Periodic Minimal Surfaces (TPMS). TPMS stand out due to their intriguing property of possessing zero-mean curvature at all points, devoid of any sharp edges or corners. This unique characteristic stems from their inherent ability to locally minimize surface area within the confines of a specified boundary [47].

The exploration of TPMS holds significant relevance within the realm of cellular materials, as these structures offer a distinct advantage in engineering applications where smooth and continuous surfaces are paramount. Their zero-mean curvature property contributes to enhanced structural stability and minimizes stress concentration points, a feature of utmost importance in the design of lightweight and resilient materials for various industries [48]. Additionally, TPMS structures exhibit remarkable potential for tailored material properties, and their incorporation in cellular materials opens up new avenues for optimizing mechanical behavior, energy absorption, and performance characteristics. TPMS are not confined solely to the realm of engineered materials; they have also been identified in the intricate designs of natural systems. Examples abound, from the delicate and iridescent films of soap bubbles [49] to the sophisticated patterns found in block copolymers [50]. Natural phenomena such as the vibrant hues adorning butterfly wings [51] and the intricate skeletal structures of sea urchins [52] further highlight the ubiquity of

TPMS in the biological world. TPMS lattice structures offer a favorable combination of specific stiffness and axisymmetric stiffness, high surface-to-volume ratios, and pore connectivity, potentially eliminating the need for surface skinning [53]. Their inherent characteristics include a notably high surface-to-volume ratio [48], ensuring efficient material utilization, as well as pore connectivity, which obviates the need for additional surface skinning [54]. These attributes hold tremendous potential for a wide array of applications, motivating countless researchers to delve into the arrangement of shapes present in natural materials, with the aim of emulating these biological marvels [55].

Existing research strongly supports the superiority of TPMS sandwich structures and bioinspired closed-cell foams over open-cell foams and random structures [48]. However, prior studies have mainly focused on analyzing the elastic properties and individual unit cell responses, rather than plastic deformation behavior, especially concerning energy absorption capacities. It's crucial to recognize that the design criteria for cellular structures differ based on their intended applications, especially for energy absorption, where impact mitigation and self-crushing behavior are vital. These structures undergo significant deformations, involving complex movements of their components. Despite their impressive mechanical performance, the literature lacks comprehensive low-impact test results and comparative finite element analysis (FEA) of various core topologies. This study aims to fill this gap by investigating the mechanical behavior and energy absorption performance of engineered sandwich panels with different core unit cell geometries through both experimental tests and numerical simulations. Furthermore, despite the substantial potential of bioinspired structures in optimizing lightweight designs, the literature offers limited investigations, with mechanical performance, modeling, and fabrication aspects of these structures yet to be thoroughly explored [56], [57].

2.6 Low-velocity impact test

Effective design and application of sandwich structures depend on a deep understanding of their constituent materials, which include face sheets, core, and adhesive, as well as a comprehensive grasp of how these structures behave under various loading conditions, spanning both quasi-static and dynamic scenarios. In particular, sandwich structures have long been acknowledged for their susceptibility to damage resulting from impacts by foreign objects

Sandwich structures have been recognized for their vulnerability to impact-induced damage resulting from foreign objects [58], [59]. Low-velocity impact studies on composite sandwich structures are crucial due to their complex nature. Our research delves into the core geometries of sandwich panels, aiming to enhance our comprehension of failure mechanisms, energy absorption, and damage characterization within these structures. The focus on low-velocity impact is strategically aligned with real-world scenarios, notably in aerospace and automotive applications, where structures are routinely subjected to mild yet repetitive impacts [17]. This choice is driven by the imperative to investigate the intricate dynamics of energy absorption and damage response under these specific conditions, ultimately bridging a critical gap in our collective knowledge.

Previous research has shown that sandwich structures while offering many advantages in their mechanical properties, are prone to impact-induced failures [60]. These failures typically lead to the degradation of energy absorption capabilities and structural stiffness, thereby jeopardizing structural integrity. Impact loads inflict significant damage on the sandwich structure, with this damage often escalating with repeated loading, including visible deformations, cracks, fractures, or even structural failure [20]. Furthermore, impact failure is a common problem that affects the strength and structural integrity of sandwich composites [24]. This issue is usually caused by the degradation of energy absorption competence and structural stiffness. The sandwich structure suffers major damage from the impact load, and the damage progressively increases with repeated loading [23]. As mentioned before, while prior research on impact has primarily focused on the analysis of impact dynamics, the characterization of impact-induced damage, and the determination of post-impact mechanical properties in composite structures, our approach sets a distinctive course. A comprehensive examination of various core geometries' modeling, specifically bioinspired geometry design, and their influence on the energy absorption capabilities of sandwich panels is undertaken, providing a more encompassing view of deformation and damage response. This approach transcends the narrower perspectives often employed in earlier studies, affording a deeper understanding of the impact's ramifications.

CHAPTER 3 : METHODOLOGY

3.1 Core design

The mechanical properties of sandwich panels are significantly influenced by the core geometry, which plays a pivotal role in determining the overall structural behavior [23]. This core geometry can be broadly categorized into two fundamental groups: stochastic and periodic designs, each further subdivided into specific configurations. Stochastic designs encompass open-cell and closed-cell foams, while periodic designs include 2D and 3D lattice structures. These design variations are illustrated in Figure 1.2 for clarity. Our study's central goal is to augment the energy absorption capacity of sandwich panels through a strategic optimization of their core geometry.

To achieve this goal, an in-depth exploration of seven distinct core topologies, each with its unique characteristics and potential implications, was conducted. These core topologies comprised three Triply Periodic Minimal Surfaces (TPMS) variants (Gyroid, Diamond, and Primitive) along with three bioinspired closed-cell foams (Tetra Radia, Mono Radial, and Tri Radial). Additionally, traditional honeycomb sandwich panels were included for comparative analysis. The nuanced interactions between these diverse core geometries and their influence on energy absorption within sandwich panels were delved into. By scrutinizing these core designs, a comprehensive understanding of the specific mechanisms through which energy is absorbed and distributed within the panel structure was sought, shedding light on potential avenues for enhancing their energy absorption capabilities.

Table 1. Dimension of the sandwich panels.

Panels	**Dimension**		
	x-direction (mm)	y-direction (mm)	z-direction (mm)
Core	100	100	40
Facesheet	100	100	5

To enhance the impact resistance and energy absorption capabilities of sandwich panels, a novel method rooted in space-filling design principles was employed. This innovative approach sought inspiration from various natural structures renowned for their inherent impact resistance capabilities. These sources of inspiration included the skull bone [39], nacreous shells [61], turtle shells [62], dentin-enamel junctions [23], and enamel. Each of these biological structures has evolved over time to withstand and dissipate impact forces, making them excellent models for creating resilient and high-performance sandwich panels. In the iterative design process for our bioinspired sandwich panels, the maximization of contact points between the core and the panel subjected to lift forces was a key consideration. This approach aimed to optimize the load-bearing capacity and energy absorption potential of the panels. The process involved fine-tuning geometric features to achieve a harmonious and efficient interaction between the core and face sheets. A notable aspect of this design approach was the careful management of relative density. Throughout the iterative modifications, a constant relative density was maintained to ensure the structural integrity of the core remained intact. This was crucial for preserving the core's ability to absorb energy while providing stability and support to the entire sandwich panel. The sandwich panel's dimensions, including its length (a), width (b), and total thickness (h), are visually outlined in Figure 2.1. For accurate reference, a coordinate system (x, y, z) was established within the panel's central plane. The study focused on square sandwich panels, with specific dimensions selected in accordance with ASTM standard D3763 [63], taking into consideration constraints imposed by testing limitations. These dimensions, as provided in Table 1, align with recognized industry standards and testing protocols, ensuring the reliability and relevance of our experimental approach. In our meticulous effort to comprehensively evaluate the impact of core geometries on sandwich panel performance, great care was taken to standardize all aspects of the panels. Each sandwich panel in the study was adjusted to feature identical unit cell dimensions and a constant relative density of 40%. This approach enabled a deeper exploration of intricate variations in unit cell deformation patterns, facilitating a more detailed and comprehensive analysis. Consequently, the design for the sandwich panels included a cellular core with a uniform height of 40 mm, complemented by 5 mm-thick face sheets. This stringent standardization process ensured consistency across all panels, subjecting every detail to scrutiny. Each panel was crafted with precision, with the unit cells at the core of the design.

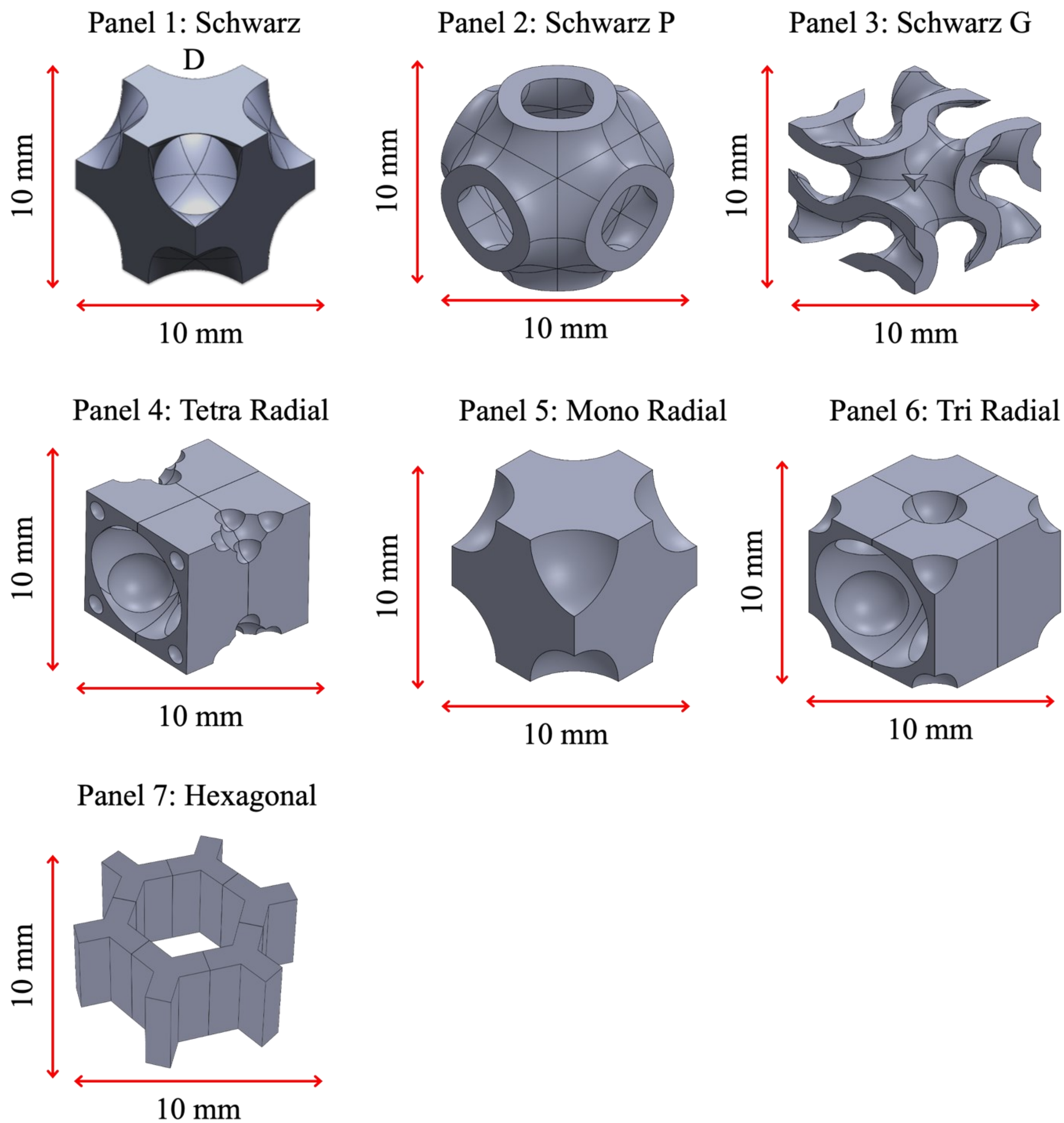

Figure 3.1. 3D Models of investigated architected unit cells.

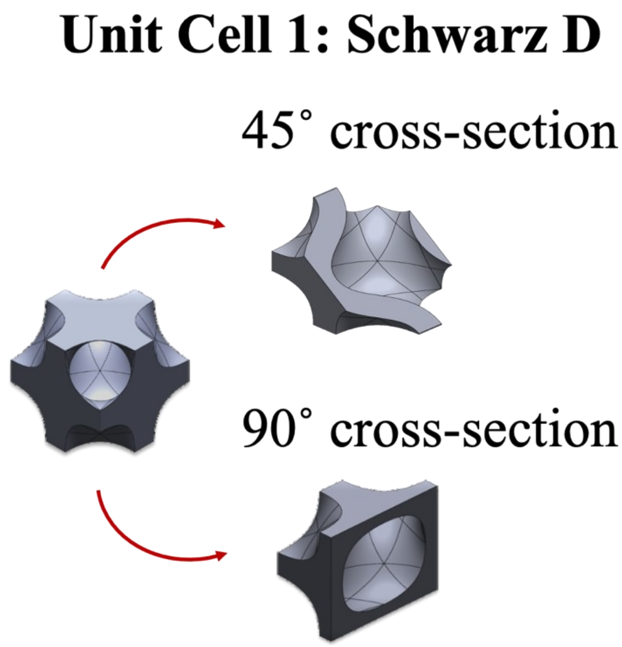

Figure 3.2. Cross-sectional and sectional views of Shwarz D.

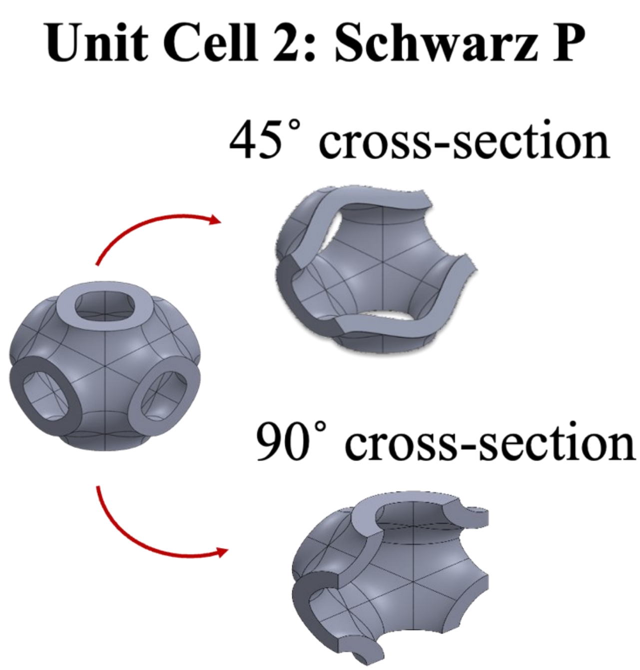

Figure 3.3. Cross-sectional and sectional views of Shwarz P.

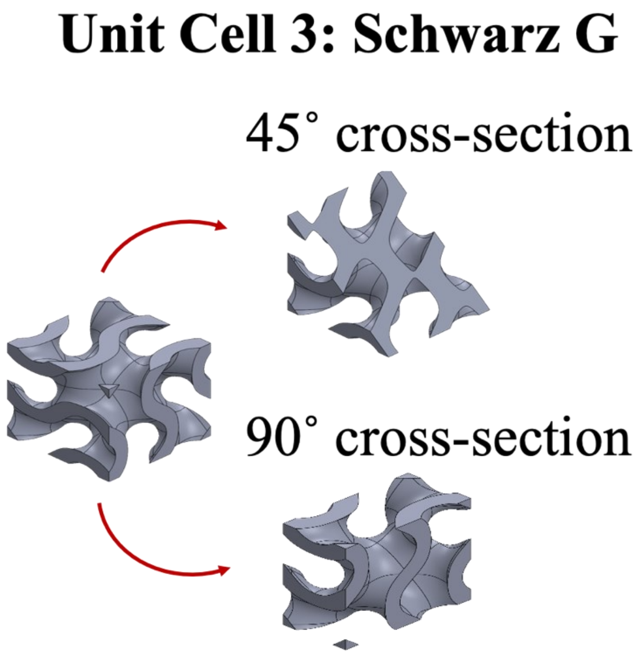

Figure 3.4. Cross-sectional and sectional views of Schwarz G.

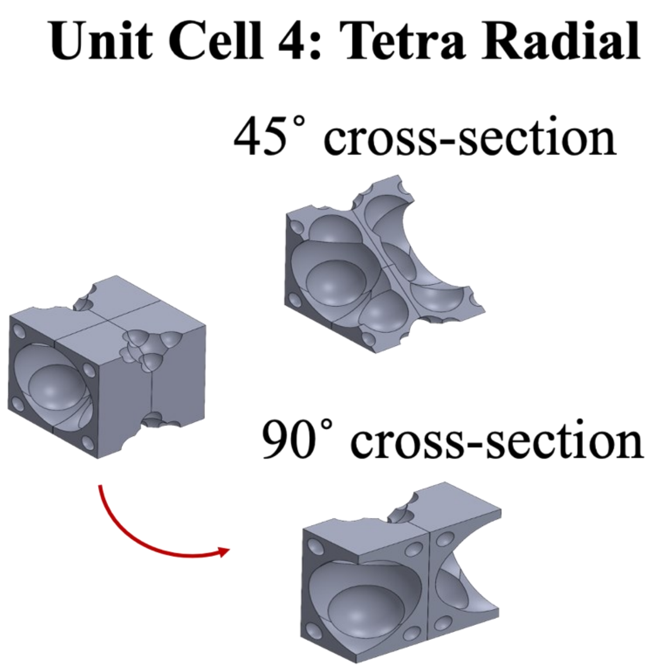

Figure 3.5. Cross-sectional and sectional views of Tetra Radial.

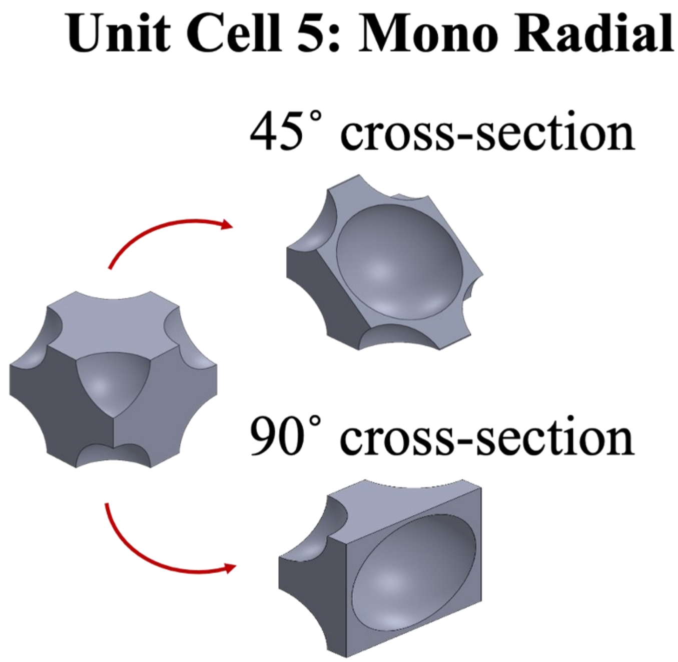

Figure 3.6. Cross-sectional and sectional views of Mono Radial.

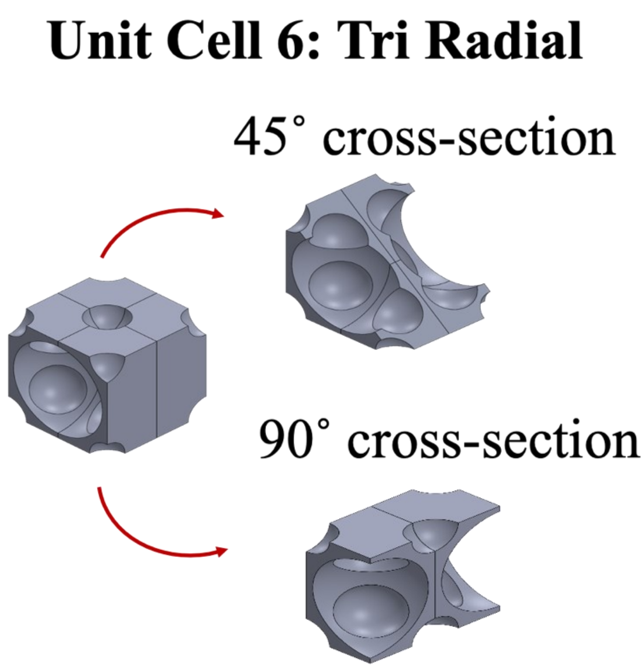

Figure 3.7. Cross-sectional and sectional views of Tri Radial.

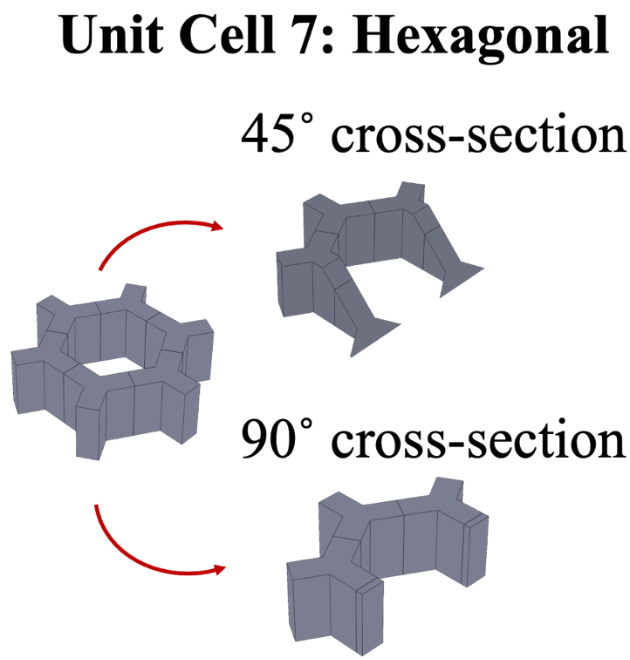

Figure 3.8. Cross-sectional and sectional views of Hexagonal.

These individual unit cells were meticulously configured, each measuring 10×10×10 mm³, and thoughtfully arranged to compose the complete sandwich panel. The arrangement of unit cells in the panel structure is visually represented in Figure 3.1, highlighting the precision in their configuration. Detailed illustrations of the unit cell designs are presented in the subsequent sections, offering comprehensive insights into the minute details of these configurations, with a specific focus on the intricate design of bioinspired closed-cell foam. To ensure a thorough understanding, two distinct section views are incorporated, shown at 45° and 90° angles in Figure 3.2 to Figure 3.8. These additional angles are included to facilitate an in-depth examination of intricate design aspects that may not be fully appreciated from the traditional front or right views. Additionally, the assembly phase of our study encompassed the fabrication of seven distinct sandwich panels, each featuring different core geometries, as illustrated in Figure 3.9. Each panel in this array measured 100×100×50 mm³ and included 10-unit cells in width, 10-unit cells in length, and 4-unit cells in height. The variety of core geometries provided a diverse dataset for our analysis.

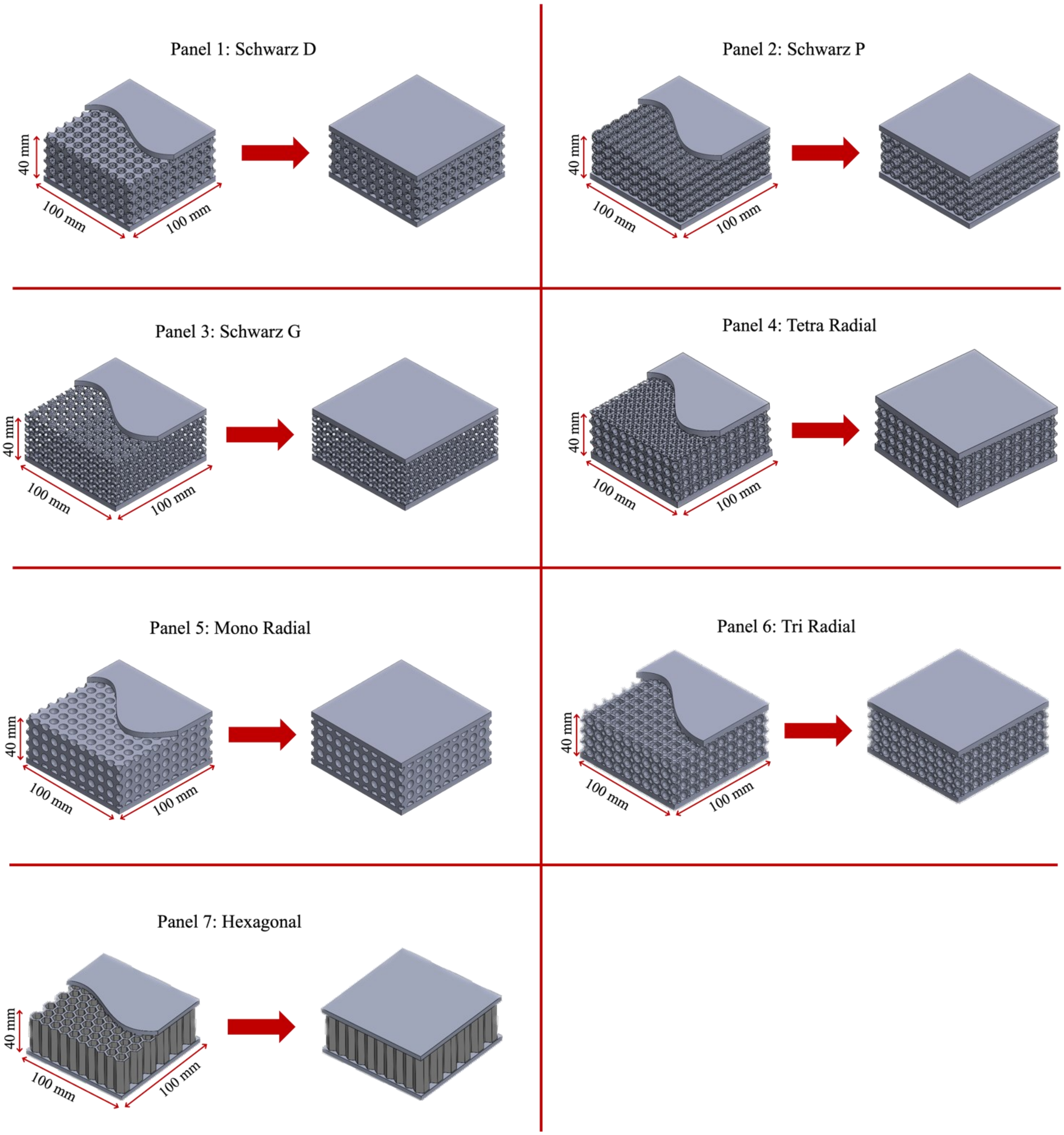

Figure 3.9. 3D architected sandwich panels (I: sectional view sandwich panel; II: sandwich panel).

3.2 Sample preparation

In the realization of our architected sandwich structures, precision 3D printing techniques were employed to ensure a high degree of accuracy and consistency, as depicted in Figure 3.10. Specifically, the MK2 3D printer, the utilized 3D printer, recognized for its reliable performance, featuring a nozzle diameter of 0.4 mm. Manufactured by the esteemed MACHINA Corp., this 3D printer operates on the fused deposition modeling (FDM) method, a well-established and widely employed 3D printing technology. The material chosen for our 3D printing was the HATCHBOX Mint Green PLA 3D Printer Filament, with a filament diameter of 1.75 mm. This material was selected for its compatibility with the FDM process and its well-regarded printing capabilities. FDM is a widely used 3D printing technology where molten polymers are extruded through an extrusion head, depositing them in the x- and y-directions, while the build table lowers the object layer by layer in the z-direction [26].

As the world of 3D printing was entered, the process was initiated by importing the CAD design (in STL file format) into the PrusaSlicer 2.5.2 slicing software. A pivotal role in the translation of the design into a Gcode file was played by this software. To create panels with a high degree of structural integrity, the choice was made for two outer shells, and a 100% filling ratio was employed to ensure robustness. The meticulous nature of the printing process is underscored by the consistent parameters that were maintained throughout. The design was subjected to a raster angle of 0°, with the layer height set at 0.25 mm. This fine-tuned layer height is a key determinant of the surface finish and accuracy of the 3D-printed structures. Additionally, a printing speed of 100 mm/s was employed to achieve the desired outcome.

During the 3D printing operation, the nozzle was heated to 215°C, elevating the material to a semi-liquid state for precise deposition. Simultaneously, the build platform was maintained at a temperature of 100°C to facilitate strong adhesion between the platform and the initial layer of printing. The significance of this step in ensuring structural integrity and the successful completion of the 3D printing process cannot be overstated. To maintain uniformity and consistency, all samples were printed in the same orientation and position. This decision was underpinned by the acknowledgment that the layer-by-layer build direction can exert a substantial influence on the mechanical response of the printed structures. Our commitment to maintaining these consistent printing practices reflects our dedication to producing results that are not only accurate but also reliable and reproducible.

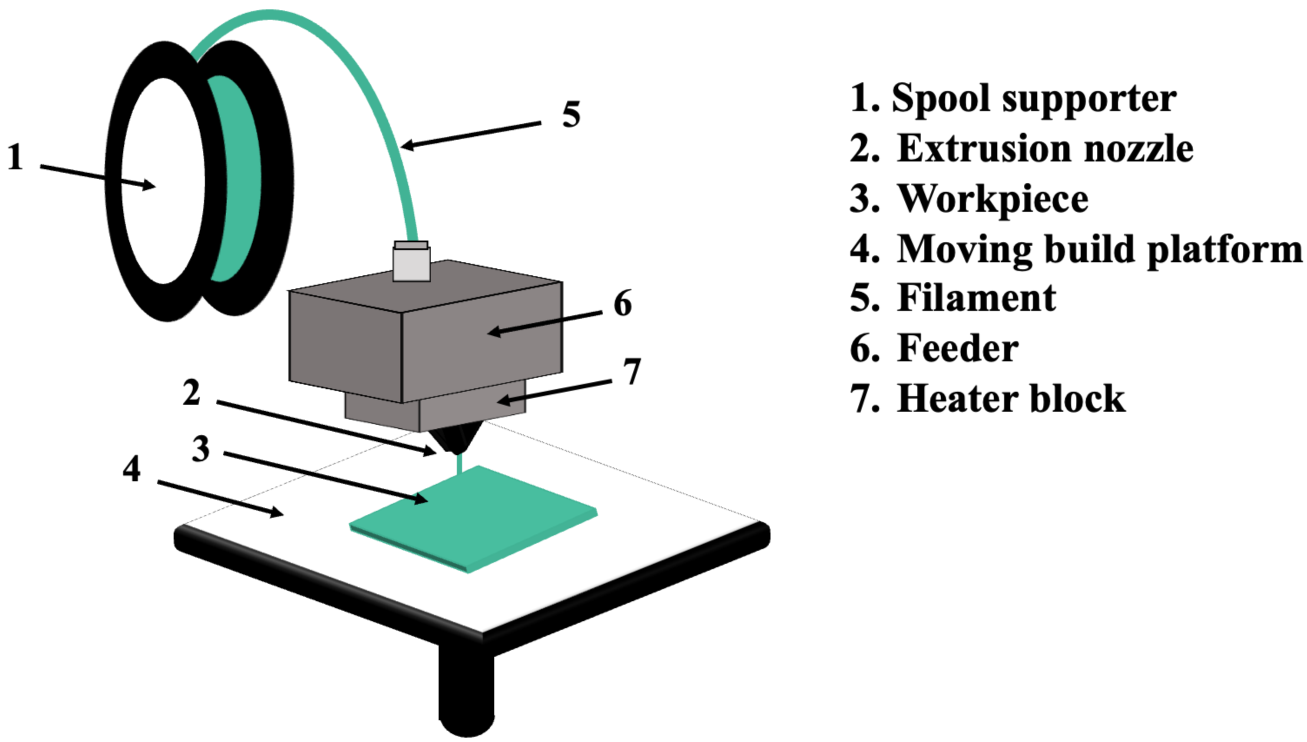

Figure 3.10. Schematic of the 3D printing fabrication process.

As depicted in Figure 3.11, our research delved into the production of 3D-printed panels that featured a diverse range of cellular cores. The intention behind this selection was to explore and compare the performance of different core types in the context of our sandwich structures. Specifically, the cellular cores employed in our 3D-printed panels encompassed three primary categories:

1. Triply Periodic Minimal Surfaces (TPMS): Within this category, three distinctive TPMS designs were studied, each offering unique geometric properties and structures. These included the Gyroid, Primitive, and Diamond designs.

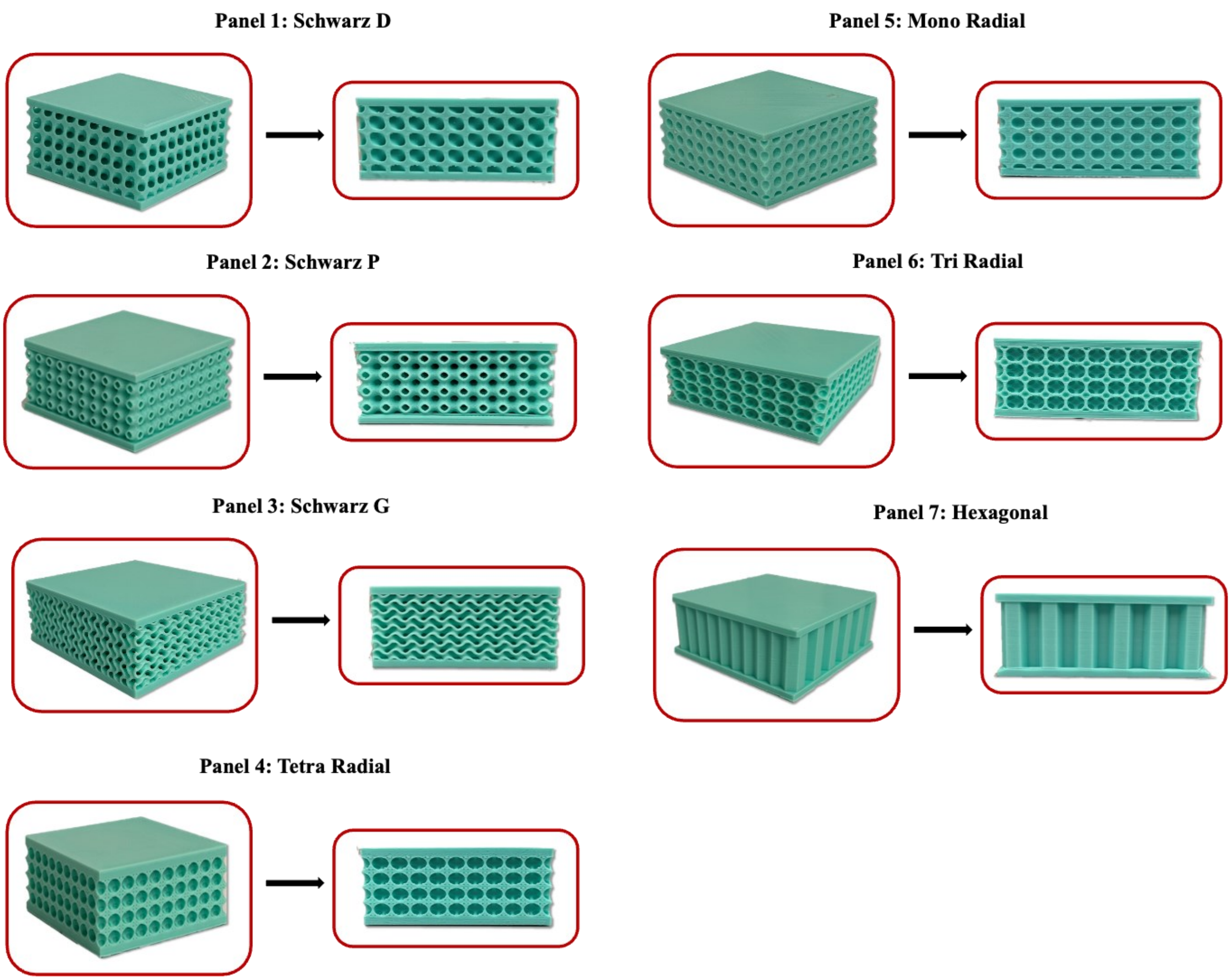

Figure 3.11. Isometric and Front View of Sandwich Panels Fabricated via SLA 3D Printing.

2. Closed-Cell Foam: Exploration was undertaken into three variations of closed-cell foam structures, each known for specific attributes and performance characteristics. These designs were named Tetra Radial, Mono Radial, and Tri Radial.

3. Honeycomb: The third category incorporated honeycomb cellular cores, which have been a conventional and well-established choice for sandwich structures. Honeycomb structures are renowned for their favorable properties, and their inclusion served as a valuable point of comparison for our study.

4. Through the utilization of this diverse array of cellular core designs, a comprehensive evaluation was aimed at regarding their respective influences on the overall performance of our 3D-printed panels. Each of these core types presented distinct features and advantages, and the study sought to elucidate the impact of these variations on factors such as energy absorption and mechanical behavior within the sandwich structures.

3.3 Material Properties

To accurately assess the mechanical properties of the sandwich panels, it is imperative to have a precise understanding of the material characteristics underlying these structures. For this purpose, tensile specimens were fabricated in the form of dog-bone shapes, adhering to the ASTM standard D638 Type IV [64], utilizing the very same material used in the production of our architected sandwich panels, as visually represented in Figure 3.12. The mechanical behavior of the 3D-printed materials, particularly properties such as Young's modulus and Poisson's ratio, can be significantly influenced by the orientation of 3D printing [65]. Therefore, a meticulous investigation into the impact of printing orientation was undertaken.

Figure 3.12. A representative optical image of the printed tensile dog-bone samples.

To explore the connection between printing orientation and material properties, tensile specimens were crafted with 100% infill at varying angles relative to the loading axis. These angles included -45/ 45° and 0°/ 90°, as elucidated in Figure 3.12. Subsequently, these specimens were subjected to tensile tests, with the experiments being conducted using an MTS mechanical tester (C43 frame) equipped with a 10 KN load cell. The orientation of 3D printing was revealed to exert a notable influence on the failure mechanisms exhibited by the dog-bone specimens during tensile loading, as illustrated in Figure 3.13. This facet of our research allowed us to gain valuable insights into how the mechanical behavior of the materials used in our sandwich panels is affected by the 3D printing orientation, a factor that is integral to our overall understanding of these materials and their performance.

Furthermore, the stress-strain curves played a pivotal role in our analysis as they were instrumental in deriving mechanical parameters of significant importance, such as Young's modulus, ultimate strength, and ultimate strain of the samples. These critical curves are presented in Figure 3.14a. The data extracted from these tests allowed us to calculate average values for Young's modulus and elongation of the dog-bone samples, which are visually represented in Figure 3.14b.

Figure 3.13. Image of 3D printed dog-bone samples after tensile test.

In the following, the mechanical properties of the filaments, as determined through tensile testing form stress-strain curves, were thoughtfully presented in Table 2. These parameters serve as direct input properties for material simulation within the Finite Element Analysis (FEA) software. This thorough investigation of material properties, achieved via comprehensive stress-strain testing, enriches our understanding of material responses to tensile loading. Furthermore, it provides essential data that significantly informs our overarching assessment of the mechanical behavior exhibited by the sandwich panels.

Table 2. Mechanical properties of the investigated sandwich panels.

Panels	**Material property**		
	Young's modulus (GPa)	Poisson's ratio	Ultimate strength (MPa)
Core	1.727	0.38	17.55
Facesheet	1.727	0.38	17.55

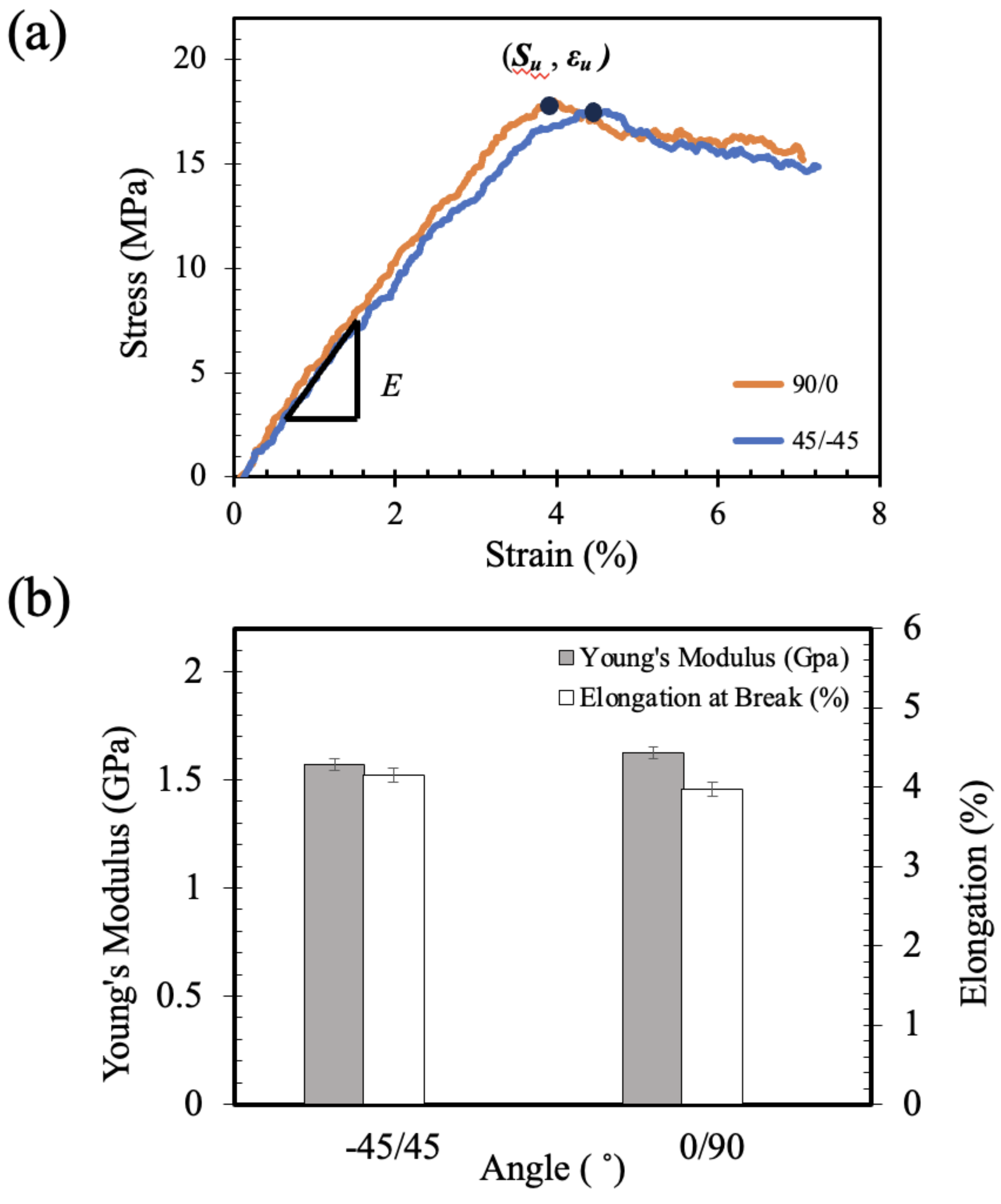

Figure 3.14. Engineering stress-strain curves of 3D printed PLA samples under tensile load; (b) Graph of Young’s modulus and elongation parameters.

3.4 Low-velocity impact tests

The dynamic energy absorption capabilities of the meta-sandwich plates were rigorously evaluated through a series of low-velocity impact tests. These assessments were carried out utilizing the advanced INSTRON 9340 Drop Test Machine, showcased in Figure 3c, conforming to the ASTM 7136 test procedure [65]. The choice of INSTRON 9340 was deliberate, as it is renowned for its precision and superior control features, ensuring the utmost accuracy in capturing impact data.

In these impact tests, an impactor featuring a 19 mm diameter and a substantial mass of 22.5 kg (2.5 kg for the holder and an additional 20 kg in the form of weights) was employed. The impactor was equipped with a hemispherical striker tip, optimized for consistent and reliable impacts. The test specimens were meticulously placed between two parallel rigid supports, each featuring a 75 mm diameter hole at their center, as demonstrated in Figure 3.15. This configuration ensured the secure positioning of the samples and eliminated any potential slippage during the experiments, thereby guaranteeing precise and repeatable results. The impactor was released with a controlled speed, precisely set at 3.91 m/s, designed to generate an impact energy of precisely 25 J. This energy level was determined as ideal for investigating the impact resistance of different samples under deformation, highlighting the machine's capability to deliver precise and controlled impacts.

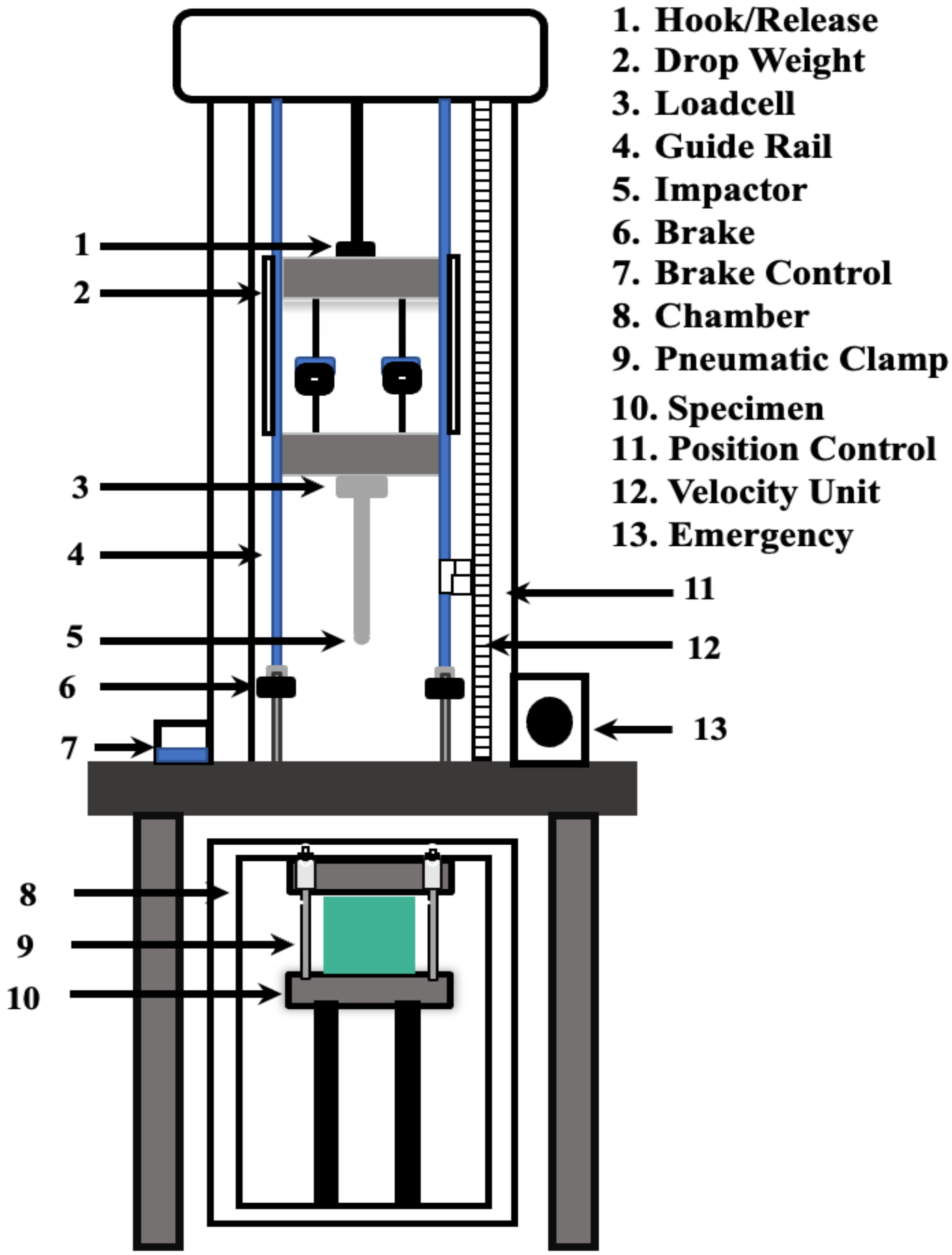

Figure 3.15. Schematic of the impact test machine configurations.

Throughout the experiment, two key parameters were meticulously measured: impact energy and impact velocity over the duration of the impact test. An exceptionally sensitive load cell was employed to capture the exact load data, allowing us to scrutinize the varying forces acting on the samples during the impact event. In parallel, a state-of-the-art velocity detector system was employed, featuring a photodetector block in conjunction with a flag to gauge the velocity of the impactor accurately. This dynamic system provided a detailed profile of the impactor's motion, ensuring that every nuance of the impact event could be captured with pinpoint precision. The entire experimental setup was thoughtfully designed and engineered to offer comprehensive insights into the deformation and energy absorption capabilities of the architected sandwich panels produced in this study. By leveraging the advanced technology and precision of the INSTRON 9340 Drop Test Machine, how these materials respond to real-world impact scenarios could be confidently and systematically assessed, yielding invaluable data that enhances the understanding of their performance characteristics.

3.5 Numerical Modeling

The finite element analysis of the low-velocity impact on architecture sandwich structures was conducted using the explicit solver of ANSYS 2022 R1, a renowned and robust commercial software package specifically tailored for this type of complex analysis. Our FEA model development consisted of several critical stages, which ensured comprehensive and accurate simulations, ultimately allowing us to gain valuable insights into the impact behavior of our architecture sandwich panels. Our modeling process commenced with the precise definition of the structural architectures and contact interfaces within the model. To accurately capture the impact dynamics, it was imperative to input the material properties for both the sandwich panel and the impactor, ensuring the model accurately represented real-world conditions. This step also entailed defining the physical and mechanical properties of the rigid impactor, which was composed of steel and treated as a rigid body. To simulate the interaction between the impactor and the sandwich panels, eroding surface-to-surface contact interfaces were incorporated. These interfaces accurately modeled the interaction between the impactor and the sandwich faces, including the core. To ensure that contact simulations were as realistic as possible, automatic single surface contact algorithms with self-interaction for each individual part were implemented.

During the simulations, a rigid mass equipped with a hemispherical head was released from a specific height, impacting the specimen at a controlled speed of 3.89 m/s. The impactor's movement was constrained in all directions except for the impacting direction, mimicking real-world scenarios accurately. To precisely represent the sandwich panels in our FEA model, boundary conditions were defined at the selected nodes situated at the upper and lower faces of the panels. These conditions were established as clamped boundaries, ensuring the panels were firmly secured and could not move during the simulations. Additionally, the interaction surfaces of the support fixture were also included in the model, featuring a circular section with a diameter of 76 mm, positioned at the central area and on the surface of the face sheets.

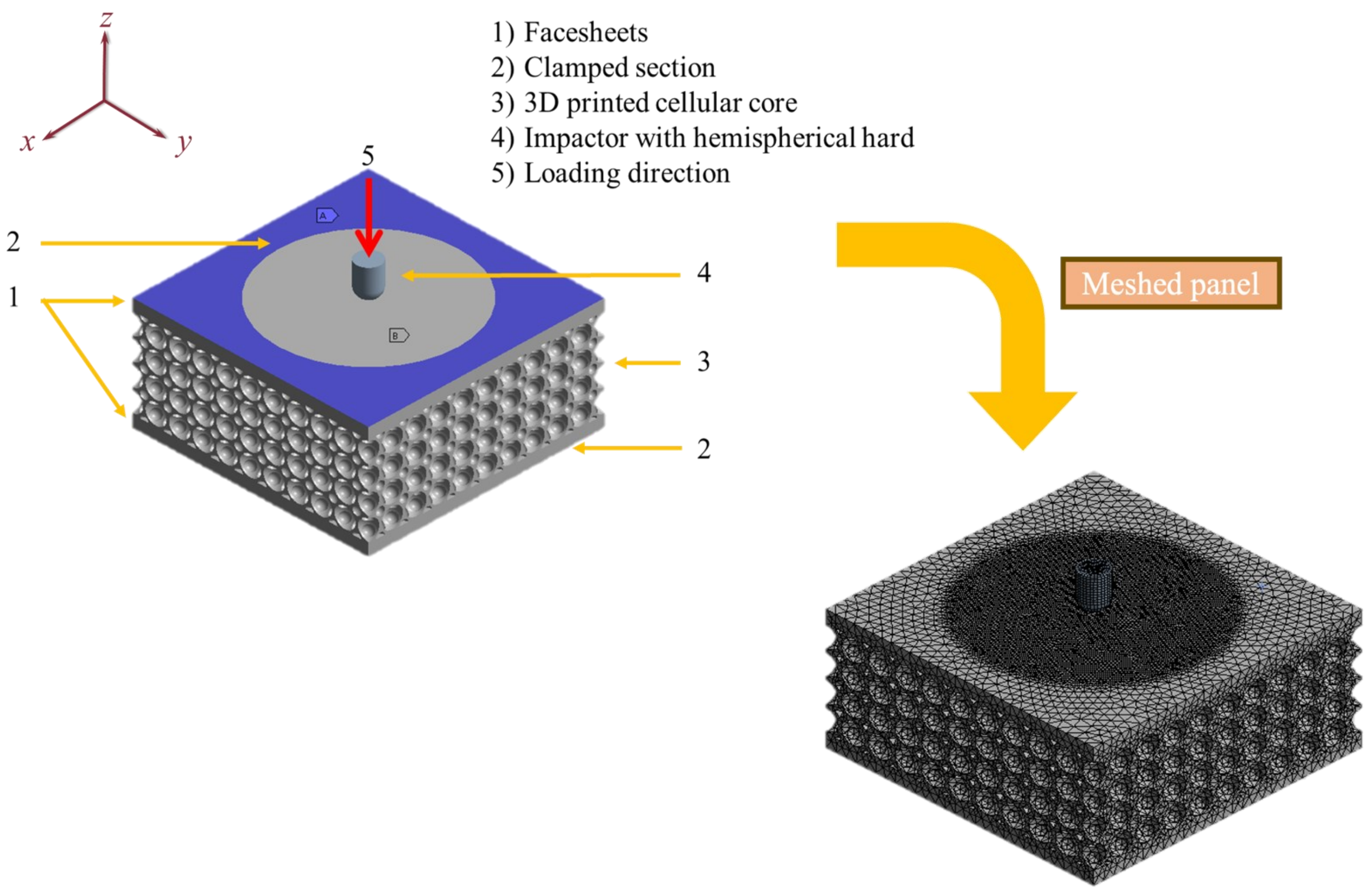

Figure 3.16. FE modeling of sandwich panels including designed part, applied boundary conditioned, and applied mesh.

The material properties of the sandwich panels were derived from the results of tensile tests conducted on dog-bone specimens, and they were implemented using a 'piecewise linear plasticity' material model with Bilinear Isotropic Hardening. This approach enabled us to capture the elastoplastic behavior accurately based on the strain curve and failure criteria derived from the tensile tests. Moreover, to maintain a delicate balance between simulation accuracy and mesh quality, a mesh convergence study was conducted. This process involved refining the mesh to ensure that the results were not significantly impacted by variations in mesh density (as shown in Figure 3.16). Quadrilateral and triangular elements were utilized to model the face sheets and core, yielding a total of 395,385 elements in the entire model. The comprehensive nature of our finite element analysis, as described above, enables us to gain a deep understanding of the behavior of our architecture sandwich panels during low-velocity impact events, supporting our pursuit of valuable insights into their performance characteristics and failure mechanisms.

CHAPTER 4 : RESULTS AND DISCUSSIONS

In this section, a comprehensive and in-depth exploration is undertaken to uncover the profound impact of different core geometries on the structural behavior, multi-hit capabilities, and energy absorption characteristics of our 3D-printed sandwich panels. The objective is to unravel the intricate interplay between core design and the panels' performance. To accomplish this, a multifaceted approach is employed, harnessing insights gained from experimental tests and numerical simulations to paint a complete picture. Numerical simulations serve as a cornerstone of the research methodology, leveraging the Finite Element Method (FEM) to create virtual models that replicate the mechanical behavior of the sandwich panels. These models are not mere abstractions; they are grounded in the material properties of PLA, meticulously extracted from the data presented in Table 2. This ensures that simulations are not divorced from reality but firmly rooted in empirical data.

Within these numerical simulations, a range of mechanical properties crucial to understanding is scrutinized. From non-dimensional deflection and stress distribution to critical buckling load and energy absorption, the performance of sandwich panels is meticulously dissected. This broad array of parameters provides a panoramic view of how various core geometries influence the panels' behavior when subjected to dynamic forces. Crucially, all simulations maintain the same foundational premise: an identical relative density of 40%. This consistent baseline allows for precise apples-to-apples comparisons, eliminating the vagaries of density variations and providing reliable and insightful results.

To uphold the utmost integrity and credibility in our evaluations, a strict regimen of uniform boundary conditions and mechanical loading parameters is maintained across all simulations. This is not a mere formality; it is an essential methodological cornerstone. The strict consistency in our approach ensures that results are directly comparable and devoid of confounding variables. Through this methodical rigor, a robust foundation for the investigation is built. This foundation, reinforced by the thoroughness of experiments and simulations, enables a comprehensive exploration of alternative core designs. The aim is to unearth their innate potential to enhance the energy absorption capabilities of 3D-printed sandwich panels. By combining insights from handson experimental testing with the precision of numerical modeling, a rich and detailed tapestry is woven, illustrating how architectural choices translate into real-world performance outcomes. With every core configuration examined, with every data point gathered, the study inches closer to expanding the body of knowledge in this field. The goal is to provide clarity and nuance to the intricate dynamics of core geometries and their role in dictating the performance of sandwich panels.

The power of the findings lies not only in the depth of understanding but also in their real-world applicability. These findings have the potential to impact industries where energy absorption is a critical consideration. The goal is not just to contribute to knowledge but also to offer practical insights that can be harnessed in the engineering of structures better equipped to handle dynamic forces. As this journey of exploration and discovery unfolds, be prepared to delve into the intricate and fascinating world of sandwich panel performance. This chapter of the research is not just about numbers and simulations; it is about uncovering the secrets that lie beneath the surface of core geometries and, in doing so, shaping the future of structural engineering.

4.1 Verification

To ensure the highest echelons of precision and reliability in our study, a rigorous validation process was meticulously conducted. The overarching objective was the establishment of a robust alignment between the finite element predictions and the empirical findings extracted from our experiments. This validation, far from a perfunctory procedure, bore the hallmark of necessity, serving as a lynchpin in guaranteeing the faithful replication of real-world outcomes in our simulations. A thorough analysis was undertaken of the mechanical responses of each specimen, encompassing an intricate comparative assessment between the results of our experimental tests and the outcomes of the explicit dynamic finite element analysis (FEA). The focus of paramount significance lay in the meticulous examination of the impact force. The force generated during our experimental trials, judiciously gauged through a sensor expertly mounted on the impactor, was subjected to rigorous comparison with the calculated force values deduced from the boundary conditions of our finite element model.

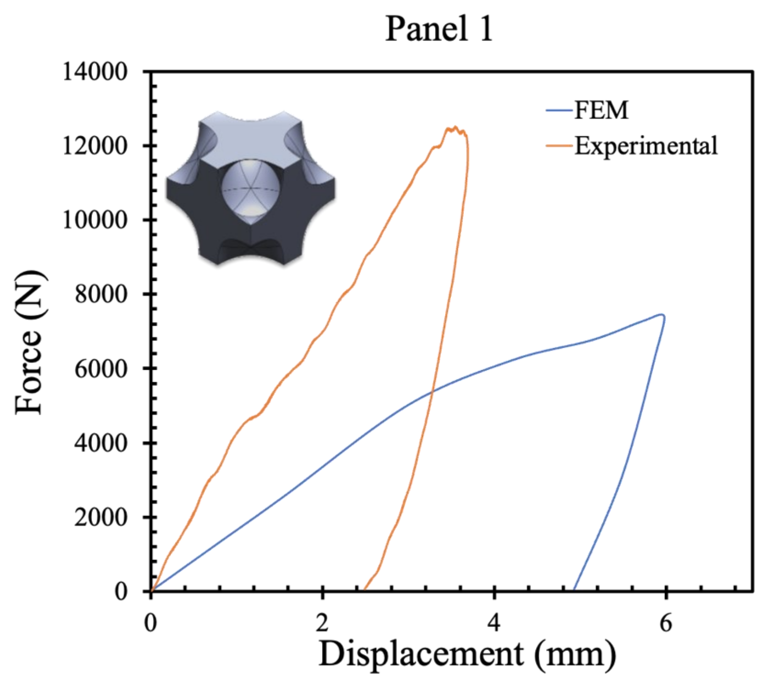

Figure 4.1. Force-displacement curves of the panel with Schwarz D core geometry.

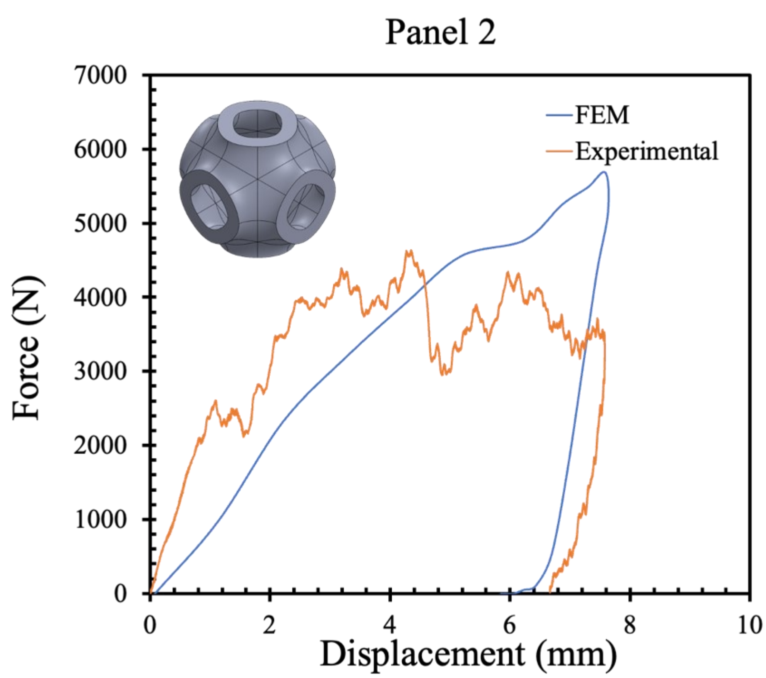

Figure 4.2. Force-displacement curves of the panel with Schwarz P core geometry.

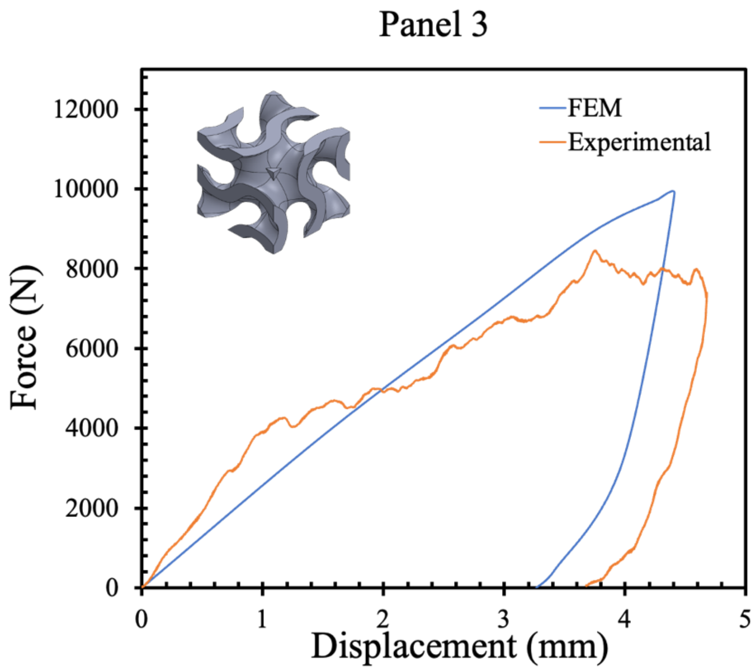

Figure 4.3. Force-displacement curves of the panel with Schwarz G core geometry.

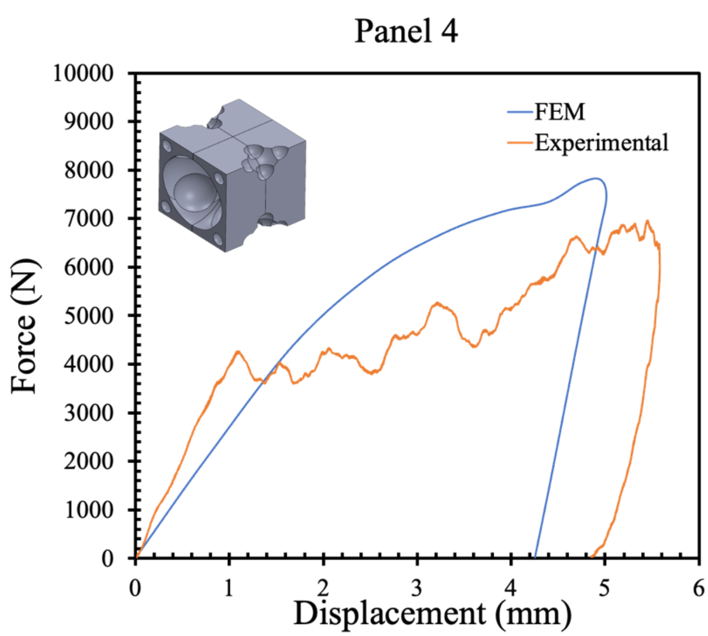

Figure 4.4. Force-displacement curves of the panel with Tetra Radial core geometry.

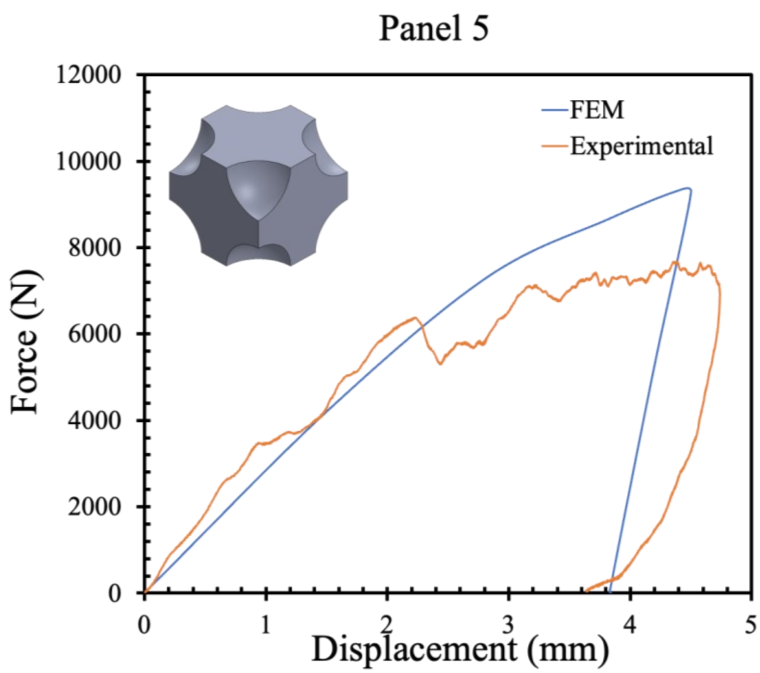

Figure 4.5. Force-displacement curves of the panel with Mono Radial core geometry.

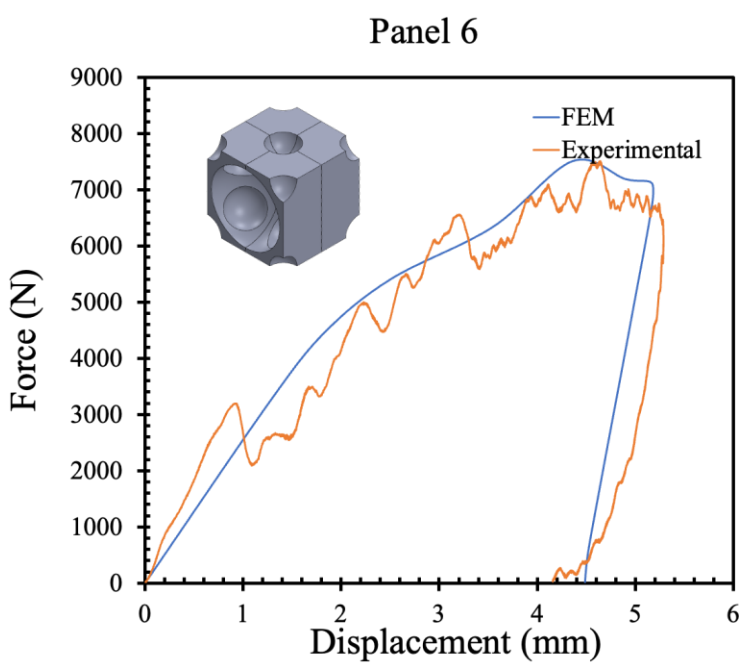

Figure 4.6. Force-displacement curves of the panel with Tri Radial core geometry.

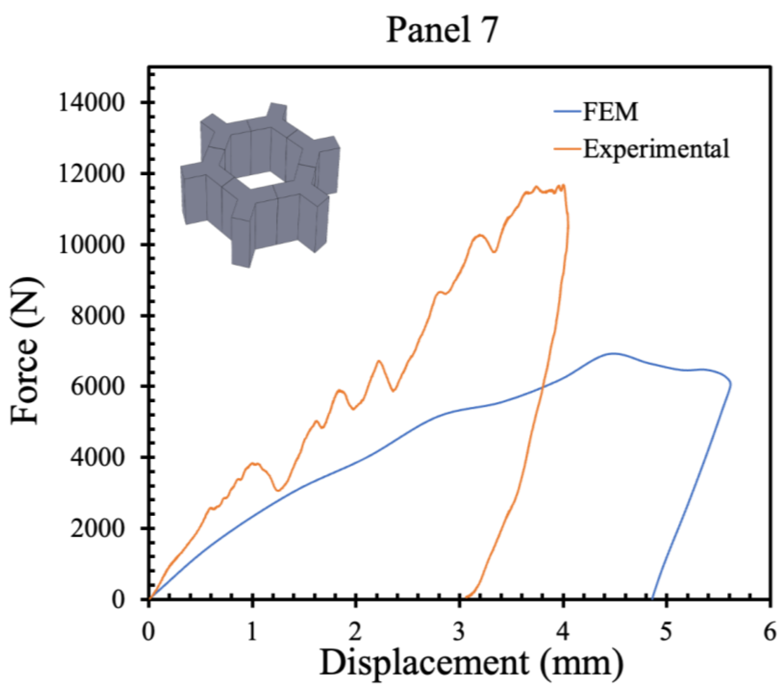

Figure 4.7. Force-displacement curves of the panel with Hexagonal core geometry.

The outcomes of this exacting validation process are presented in Figure 4.1 to Figure 4.7, where the force-displacement histories of our 3D printed sandwich panels are expounded upon. These findings bear profound implications, casting a brilliant light on the fidelity and precision of our simulations in replicating real-world structural behavior. Across a gamut of panels, including those embedded with TPMS, novel closed cell foam, and hexagonal cores, a remarkable alignment stands out.

The peak load, the overarching trend in force response, and the deflection all manifest striking consonance between the two domains. This robust congruence not only serves as a testament to the reliability and precision of our simulations in faithfully mirroring real-world structural behavior but also underscores our commitment to academic excellence. Nevertheless, as is customary in the complex landscape of comprehensive research endeavors, nuanced distinctions surface. Notably, disparities come to the fore in the cases of panel 1 and panel 7. The origins of these variations can be attributed to the specific contact points where the impactor interfaced with the samples during its descent, forging contact with the face sheets of the sandwich panels. In cases where the trajectory of the impactor led to contact with areas housing struts and walls beneath the surface, it gave rise to larger contact forces and yielded smaller deflections.

This phenomenon exerted influence on the results in both the experimental and FEA domains, thereby giving rise to discernible disparities in the force-displacement profiles for panel 1 and panel 7. Moreover, an unmistakable pattern emerges as a deeper exploration of the results is undertaken. Up to the point of yielding of the sandwich panels, a remarkable consistency is maintained in the force-displacement curves between the numerical and experimental findings. This consistency, far from being a triviality, is a formidable affirmation of the potency of our simulations in faithfully replicating real-world behavior. It underscores the precision and mastery inherent in our academic pursuit. However, post-yielding, a certain deviation becomes manifest. This deviation is primarily attributable to the utilization of the elastic-perfectly plastic constitutive law (Bilinear Isotropic Hardening) within our FEA.

As displacement along the X-axis continues to ascend, the experimental results provide illuminating insights into the structural failures of platen struts, which, in turn, trigger marked drops in the force-displacement profiles. The validation process, transcending mere formality, emerges as a pillar of confidence, buttressing trust in the accuracy and reliability of the multi-unit-cell model. With this robust foundation firmly in place, the threshold of further investigations and a comprehensive evaluation of the mechanical behavior and energy absorption capabilities of our 3D printed sandwich panels is reached, particularly in the context of varying core configurations. These findings transcend numerical data and embody a bridge between theory and the tangible realities of the physical world. Through these rigorous validations, the endeavor is to illuminate the path forward for engineering structures that are equipped to handle dynamic forces with unwavering precision and assurance.

Table 2 presents a comprehensive analysis of the critical parameters that underpin the structural behavior of 3D-printed sandwich panels. These parameters include maximum force, deflection characteristics, and the depth of dents. This comprehensive evaluation is derived from a judicious combination of experimental tests and finite element analysis (FEA). It is noteworthy that the examination of these parameters forms a critical aspect of our investigation into the dynamic response of 3D-printed sandwich panels under different conditions. Upon a meticulous review of the data presented in Table 2, an intriguing consistency emerges between the results obtained through experimental trials and the predictions derived from FEA. In most instances, the disparities between these two methodologies remain within an approximate margin of 10%. Such synchrony underscores the reliability and precision of our FEA simulations in mirroring real-world structural behaviors. However, a substantial divergence in outcomes becomes conspicuous in the case of panel 1, which incorporates Schwarz D unit cells, and panel 7, characterized by hexagonal unit cells, particularly in terms of the maximum force parameter. This disparity can be ascribed to the precise point of impact during the experimental trials.

It is essential to highlight that, in the context of these specific panels, the point of impact during experimental testing coincides with the section containing a solid core. In contrast, our FEA simulations presuppose a scenario in which the impact occurs upon the hollow core beneath the panel's outer surface. This disparity in impact locations plays a pivotal role in comprehending the marked variation in the applied load. Notably, a strong agreement surfaces when assessing the deformations exhibited by these two panels when subjected to equal applied energy. Furthermore, a set of other contributing factors demand thoughtful consideration when elucidating the marginal differences between the outcomes generated by simulations and experimental trials:

(a) The utilization of an elastic-perfectly plastic constitutive law within numerical FEA simulations introduces the potential for deviations, especially when the deformation surpasses the elastic threshold. This nuanced distinction adds a layer of complexity to the behaviors exhibited by the panels under load.

(b) The intricacies of the Fused Deposition Modeling (FDM) technique in 3D printing, marked by the deposition of molten layers along the z-axis, give rise to inherent microscopic layering in the final product. It is noteworthy that within the confines of our FEA setup, a simplified representation is employed, assuming perfect layer bonding. This assumption tends to slightly overestimate the structural rigidity and resilience of the panels [21].

(c) Our current FEA framework operates under the presumption of isotropic attributes for 3D-printed PLA materials. The unique layering process confers orthotropic properties upon these materials, a vital aspect that remains unaccounted for in the present analysis. This disparity in material properties further adds to the nuanced variations observed in the results.

Table 3. Comparison between FEA and experimental results of the 3D-printed sandwich panels subjected to low-velocity impact loading.

Core topology		**Maximum load (N)**		**Maximum deflection (mm)**		**Dent depth (mm)**	
Panel No.	Core architecture	FEA	Experiment	FEA	Experiment	FEA	Experiment
1	Schwarz D	7401	12518	5.91	3.68	4.92	2.48
2	Schwarz P	5901	4635	7.63	7.57	5.93	6.66
3	Schwarz G	9878	8455	4.40	4.67	3.26	3.67
4	Tetra Radial	7939	6966	5.01	5.58	4.25	4.85
5	Mono Radial	9478	7677	4.49	4.74	3.84	3.63
6	Tri Radial	7568	7500	5.10	5.28	4.48	4.15
7	Hexagonal	6936	11698	5.60	4.05	4.85	3.06

In summary, the exhaustive comparative analysis of experimental and FEA results, as thoughtfully assembled in Table 2, serves as a lens through which to scrutinize the intricate facets that govern the mechanical response of 3D-printed sandwich panels under varying core configurations. This pursuit transcends mere data analysis; it stands as a testament to our deep-seated commitment to advancing the understanding of structural mechanics. Additionally, the two decimal places in Table 2 reflect the precision of our experimental measurements, indicating accuracy to the hundredths of a unit. Our experiments were meticulously conducted with careful instrument calibration and controlled testing conditions to minimize sources of error. While minor variations between FEA and experimental results may exist, these are mainly attributed to experimental error. In the forthcoming discussions, the precision of each data point will be considered, working towards further improving precision in future research.

Furthermore, the progression of failure stemming from impact-induced damage is clearly delineated in the FE model (see Figure 4.8). Given that the sandwich panels were fabricated from PLA and subsequently cut using a saw, causing localized melting and rendering the damage zone areas less discernible, the FEA simulations were instrumental in exploring additional details and elucidating the influence of core topologies on mechanical properties.

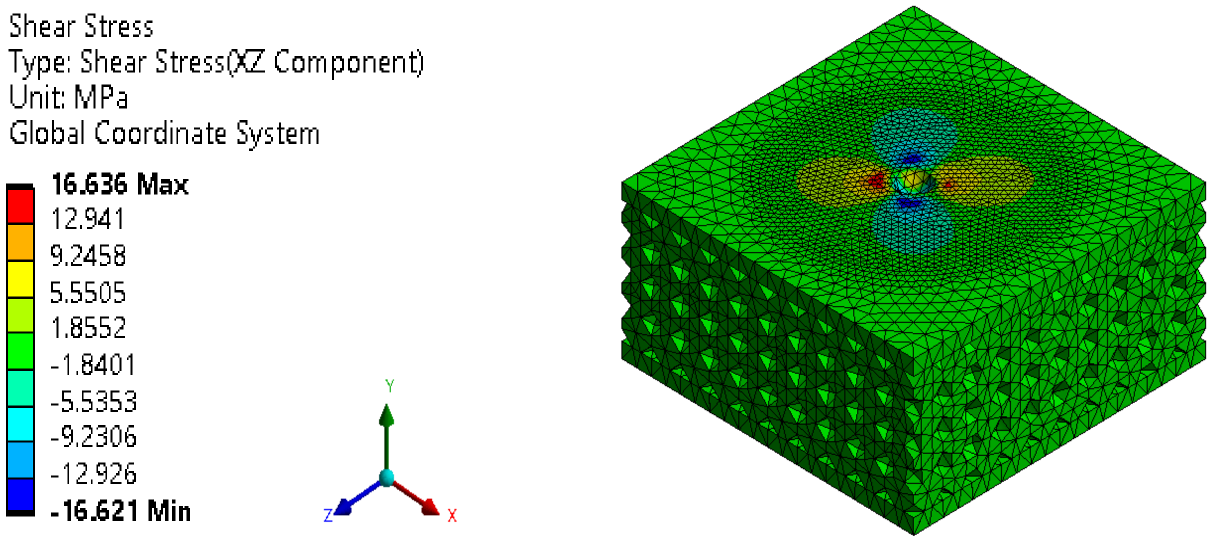

Figure 4.8. Simulation results for the low-velocity impact: Shear damage view.

As illustrated in Figure 4.8, the results underscore the significant role of shear forces in the formation of damage areas resulting from impact events. Figure 4.8 shows the manifestation of delamination effects and their direct correlation with shear zones. It becomes apparent that the highest shear forces are concentrated in the near location of the impact point, where the impactor contacted the surface, initiating face-sheet cracking. Nevertheless, it's noteworthy that damage also propagates both horizontally and vertically, extending beyond the point of initial impact. While this damage was observable in several of the tested panels, its extent was notably less pronounced than what the model revealed. Figure 4.9 visually depicts the out of plane deformation configurations observed through FEA. Notably, the deformation characteristics of the cellular core align with the visual data obtained from experimental images.

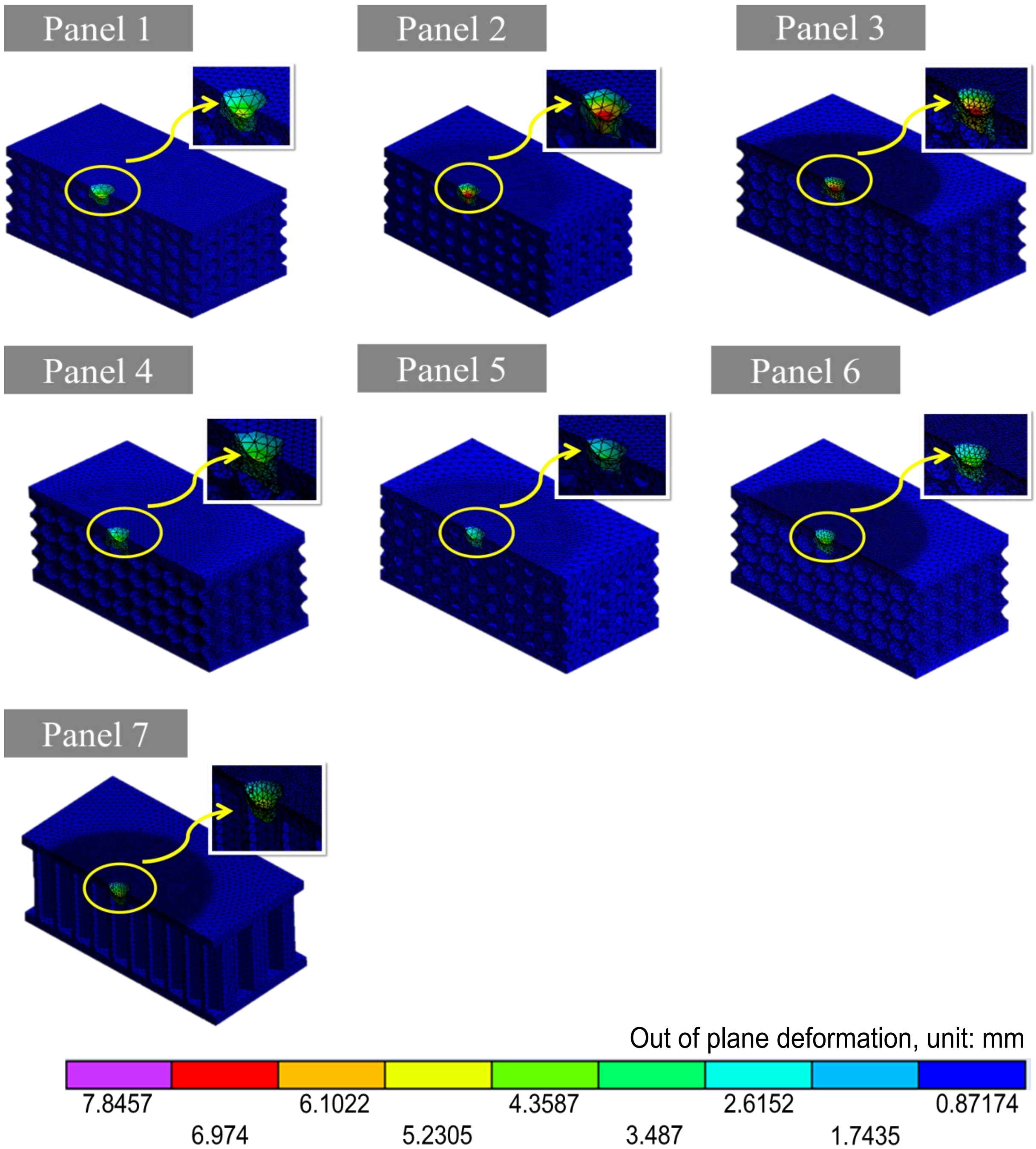

Figure 4.9. Simulation results for the low-velocity impact: Out- of plane deformation with visible damage zone area.

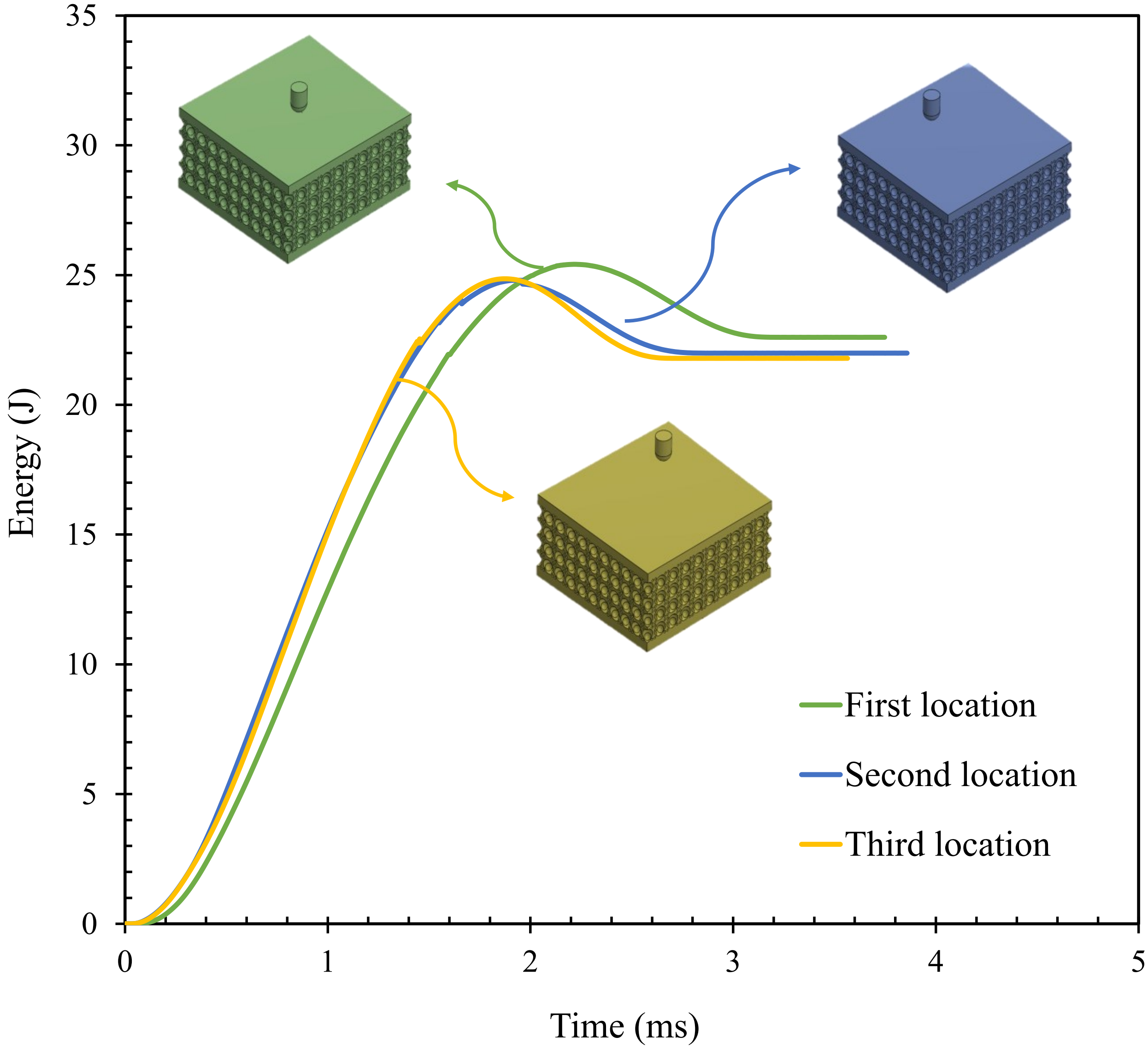

Figure 4.10. Analysis of the force-displacement curves of 3D-printed panels.

This validation process enhances the confidence in the accuracy and reliability of the multi-unit-cell model, providing a solid basis for further investigations and a comprehensive evaluation of the mechanical behavior and energy absorption capabilities of the 3D-printed sandwich panels with varying core configurations. The impactor was deliberately released onto the panel's surface at various positions, as illustrated in Figure 8a, including the following locations: the first location of impact at the center of the top face-sheet, the second location between the center and the side of the top face-sheet, and a third location to the center and the corner of the top face-sheet.

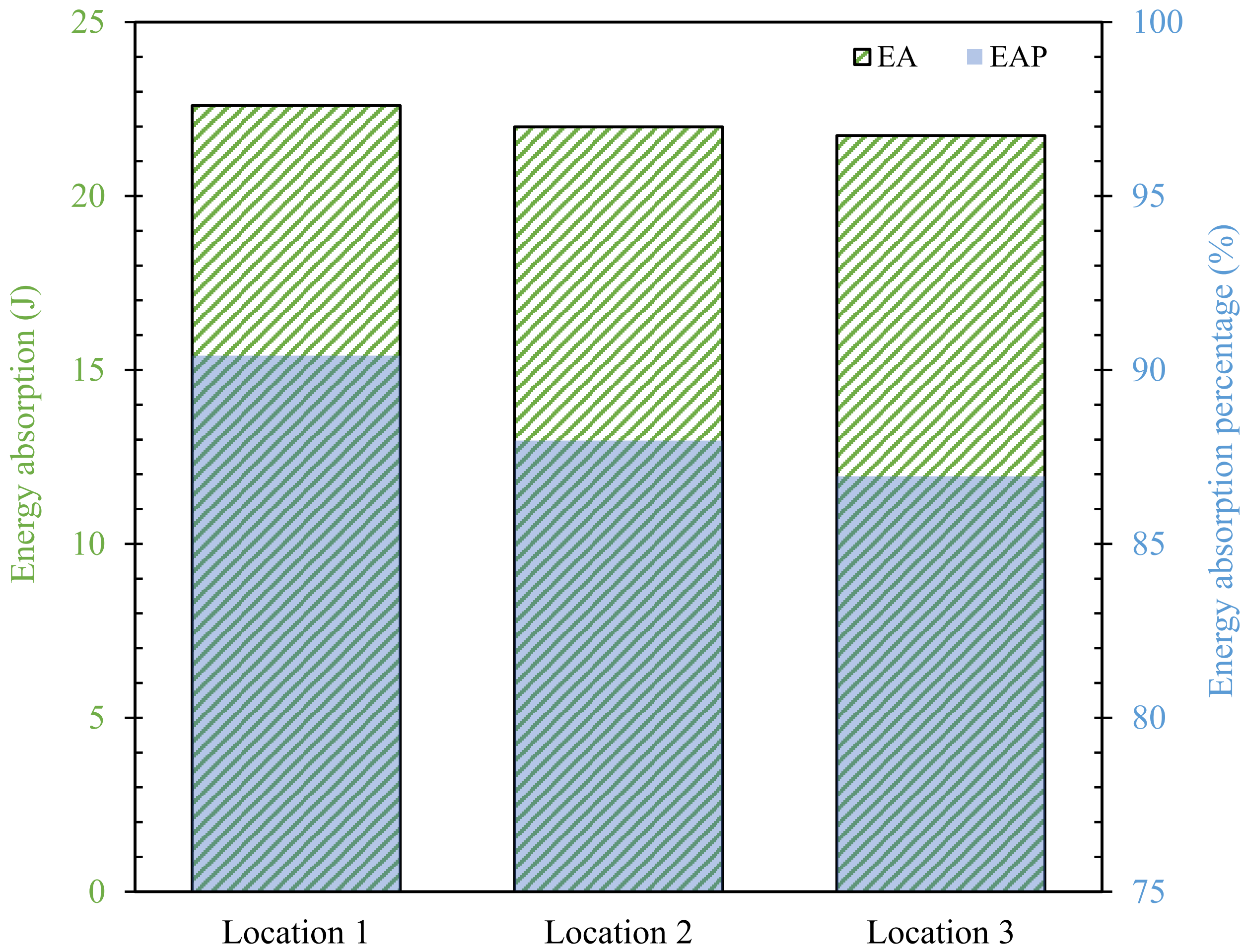

Figure 4.11. Simulation results of panel 4 under low-velocity impact at different locations: Energy and energy absorption performance.

A comprehensive overview of the results is presented in Figure 4.11. Herein, the energy performance is defined based on the ratio of the values below.

$$\text{Energy Performance: } \frac{\text{Absorbed Energy}}{\text{Maximum Impact Energy}}$$

Significantly, the energy absorption performances calculated for these scenarios revealed that the placement of the impactor had a negligible impact on the panel's energy absorption capacity, with values approximating 90% for the first location, 88% for the second location, and 87% for the third location. This finding underscores the robustness of panel 4's energy absorption capabilities across different impact locations.

4.2 Effect of core topology on energy absorption performance

Figure 4.12 graphically represents the force-displacement characteristics obtained through experimental testing of diverse 3D-printed sandwich panels, each of which comprises $10 \times 10 \times 4$ unit cells. These empirical findings underscore the substantial influence of core topology on the force-displacement responses. It is evident that Panel 1, characterized by a Schwarz D unit cell configuration, exhibits a marginally higher maximum contact force and diminished deflection. In contrast, Panel 2, incorporating a Schwarz P unit cell arrangement, presents the lowest contact force alongside the highest deformation. Notably, the sandwich panels with Schwarz D core topologies demonstrate an elevated load-carrying capacity and greater stiffness. This attribute, with its inherent potential to bolster structural stability and augment load-bearing capabilities, holds significant promise for applications necessitating such attributes. Concurrently, the graphical representation in Figure 4.12 emphasizes that sandwich panels featuring Schwarz P core topologies exhibit enhanced flexibility, enabling them to accommodate larger deformations under external loads.

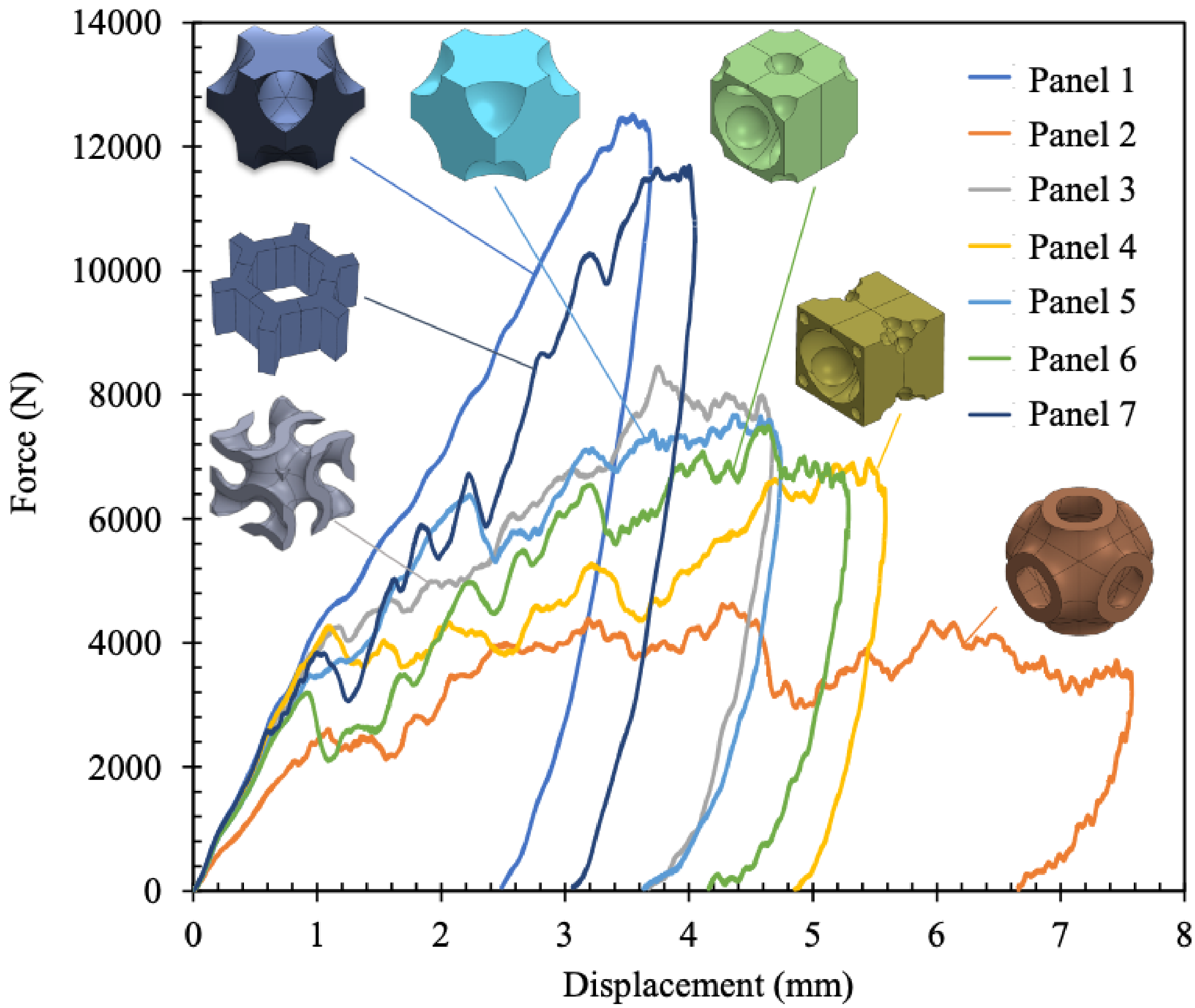

Figure 4.12. Comparative analysis of the force-displacement curves for the 3D-printed sandwich panels.

Furthermore, Figure 4.13 provides a comprehensive comparison of the damage zones observed in architected sandwich panels, each possessing a relative density of 40%, when subjected to impact energies of 25 J. It is discerned that Panel 2 manifests a broader and deeper damage zone compared to its counterparts. This observation is substantiated by the strong correspondence between the damage zone areas and contact forces obtained from finite element simulations and empirical experimentation.

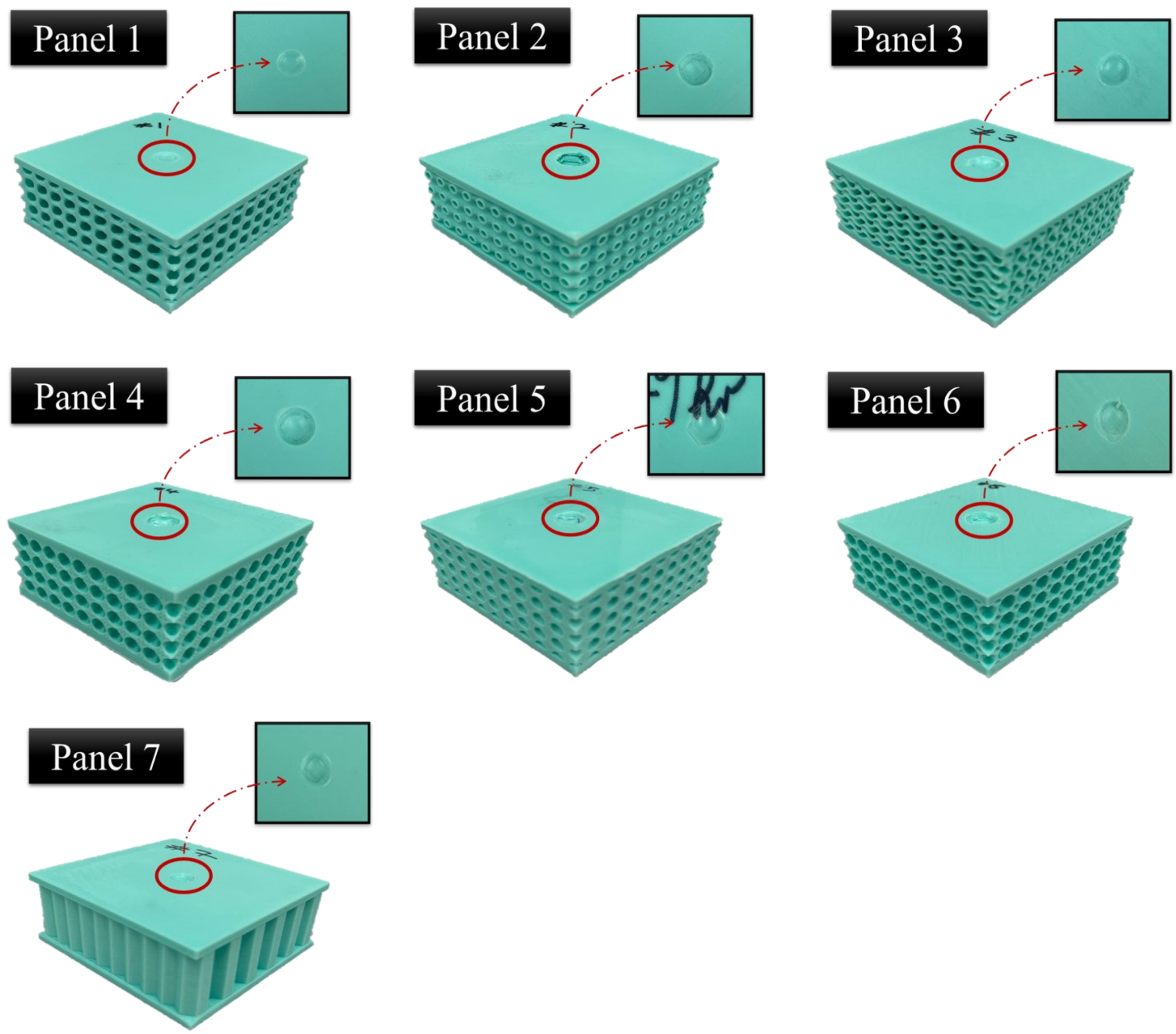

Figure 4.13. Evaluation of damage zones in impacted architected 3D-printed panels.

An attractive and compelling pattern emerges when scrutinizing the behavior of panels beyond panel 2 during impact testing. Notably, a consistent trend is observed wherein panels succeeding panel 2 consistently exhibit the largest deflection and the smallest contact force. This trend assumes particular significance, suggesting a common and distinctive behavior shared among these panels in terms of energy absorption. Of particular significance are panels 4 and 6, both categorized as bioinspired designed sandwich panels. Panel 4, designed with Tetra Radial unit cells, demonstrates a mechanical response after panel 2 under impact testing that closely mirrors the larger deflection and smaller contact force observed after panel 2. Remarkably, panel 6, featuring Trio Radial unit cells, which sequentially follows panel 4 and falls within the domain of bioinspired designs, consistently maintains this behavior. Both panels display analogous characteristics with reduced contact forces and increased deflections.

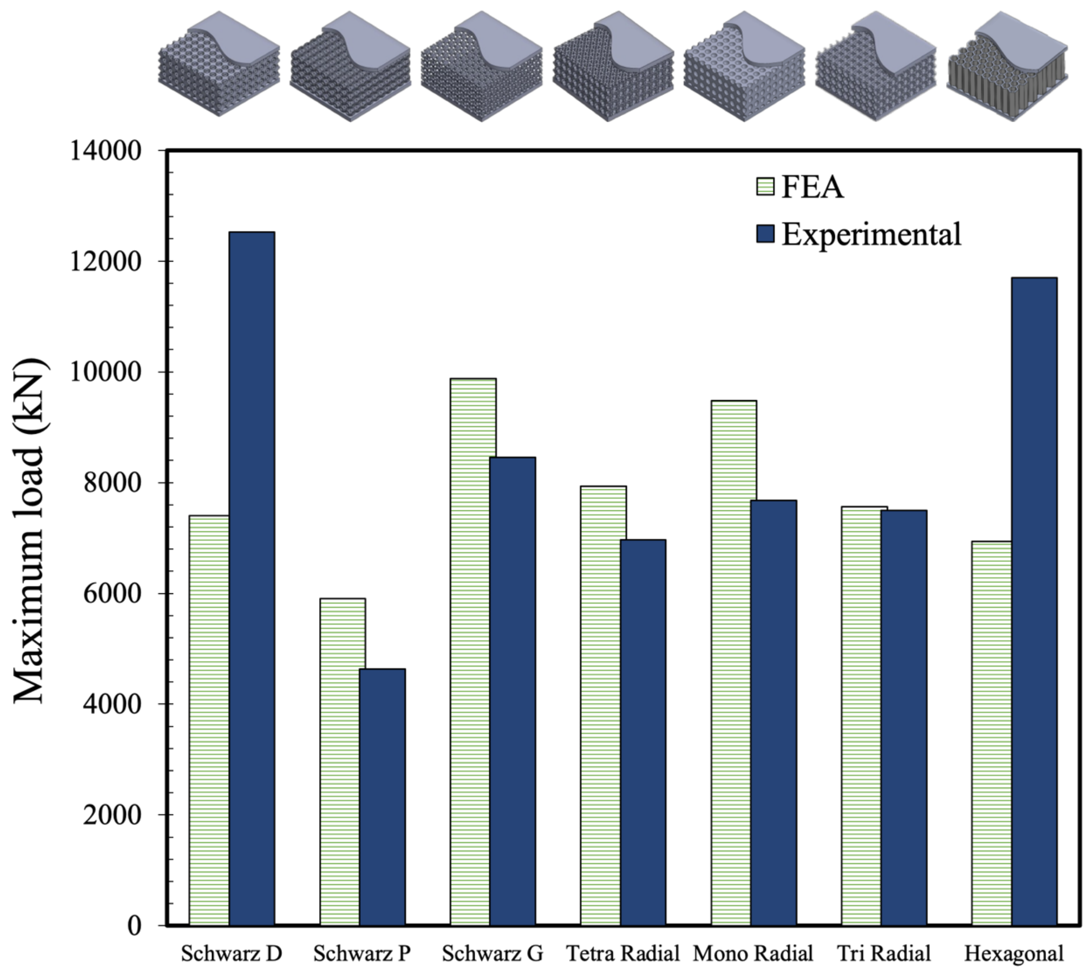

Figure 4.14. Analysis of the investigated sandwich panels: maximum load.

This striking coherence observed across these two distinct, yet bioinspired sandwich panel configurations underscore a consistent mechanical reaction intrinsic to this subset of studied designs. This uniformity in results not only adds further validity to the findings but also accentuates the impact of specific core designs on the response of panels subjected to impact testing. Additionally, Figure 4.14 to Figure 4.17 presents a comprehensive analysis of the outcomes derived from experimental impact tests on the 3D-printed sandwich panels. These results have been meticulously cross-referenced with the data presented in Table 3, ensuring their alignment. Specifically, when examining the maximum deflection depths of the assessed sandwich panels under low-velocity impact testing, a salient observation surface.

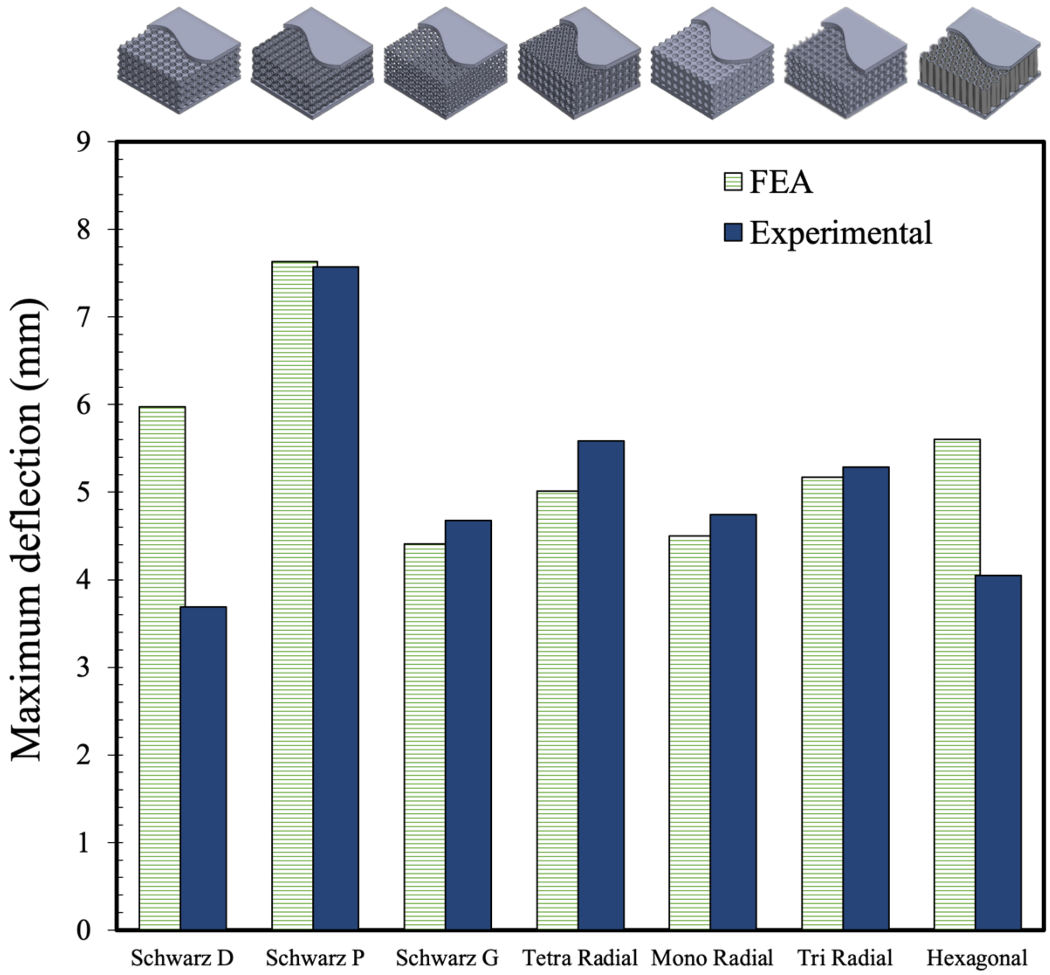

Figure 4.15. Analysis of the investigated sandwich panels: maximum deflection.

Panel 2 is characterized by a substantial deflection depth, measuring approximately 7.57 mm. This constitutes a noteworthy 75% increase in deformation depth, as corroborated by the information in Table 3, in contrast to the remaining panels subjected to an equivalent applied energy condition. Simultaneously, Figure 4.14 highlights that Panel 2 exhibits the lowest recorded contact force, measuring around 4.63 kN, marking a substantial 60% reduction when compared to the contact forces observed in the other panels. In stark contrast, Panel 1 records the highest measured contact force, registering approximately 12.52 kN – a value nearly threefold greater than that borne by Panel 2. Furthermore, the deformation length in Panel 1 is the most modest among the panels, measuring approximately 3.69 mm, precisely representing half of the deformation depth experienced by Panel 2.

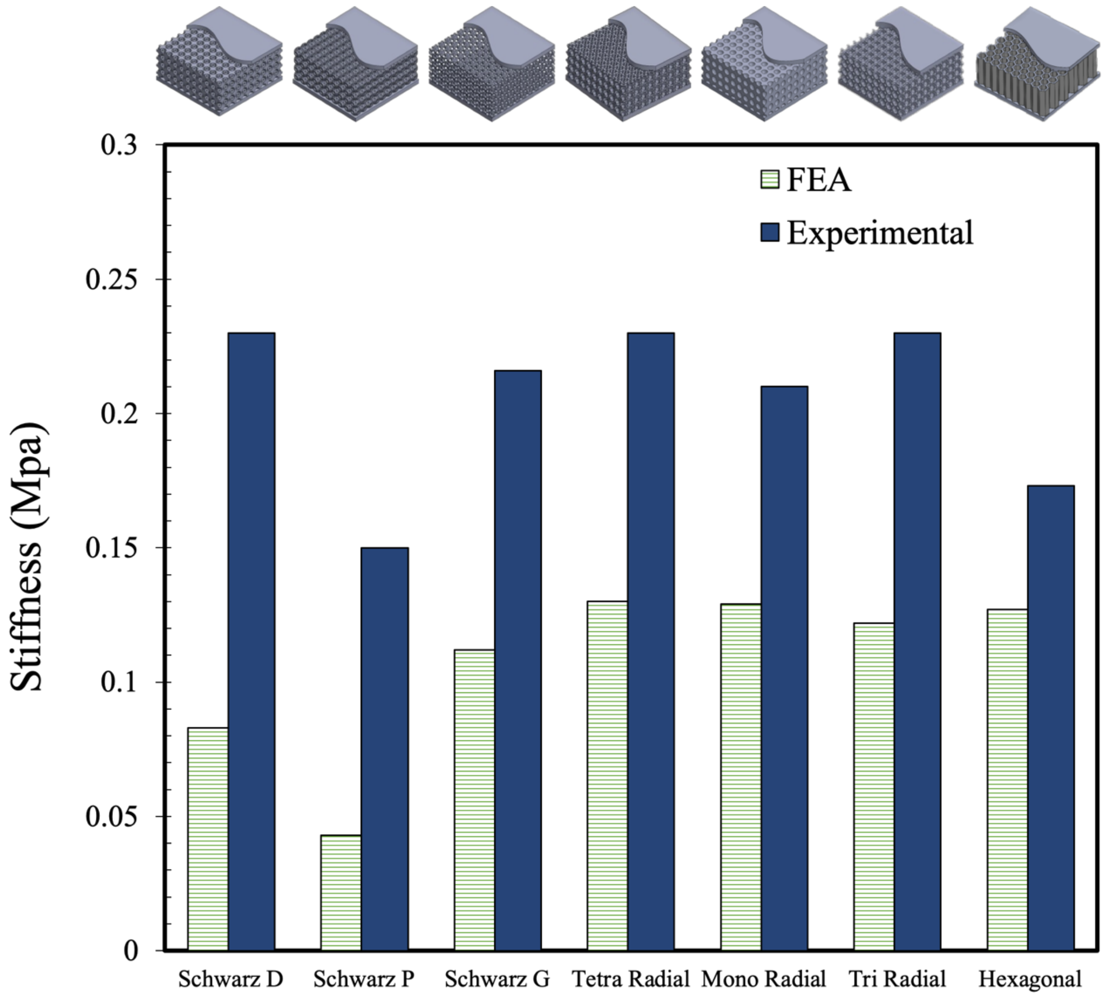

Figure 4.16. Analysis of the investigated sandwich panels: stiffness.

As reflected in Figure 4.17, these findings remain consistent with the observations concerning the dent depth of the analyzed sandwich panels. Notably, Panel 2 emerges as the most severely affected, exhibiting a dent depth of 6.66 mm, surpassing the dent depths of the other panels under examination. Additionally, when Panel 2 is compared to Panel 1, which manifests the lowest dent depth at approximately 2.49 mm, a substantial difference of roughly 2.5 times in the extent of the damaged area becomes evident.

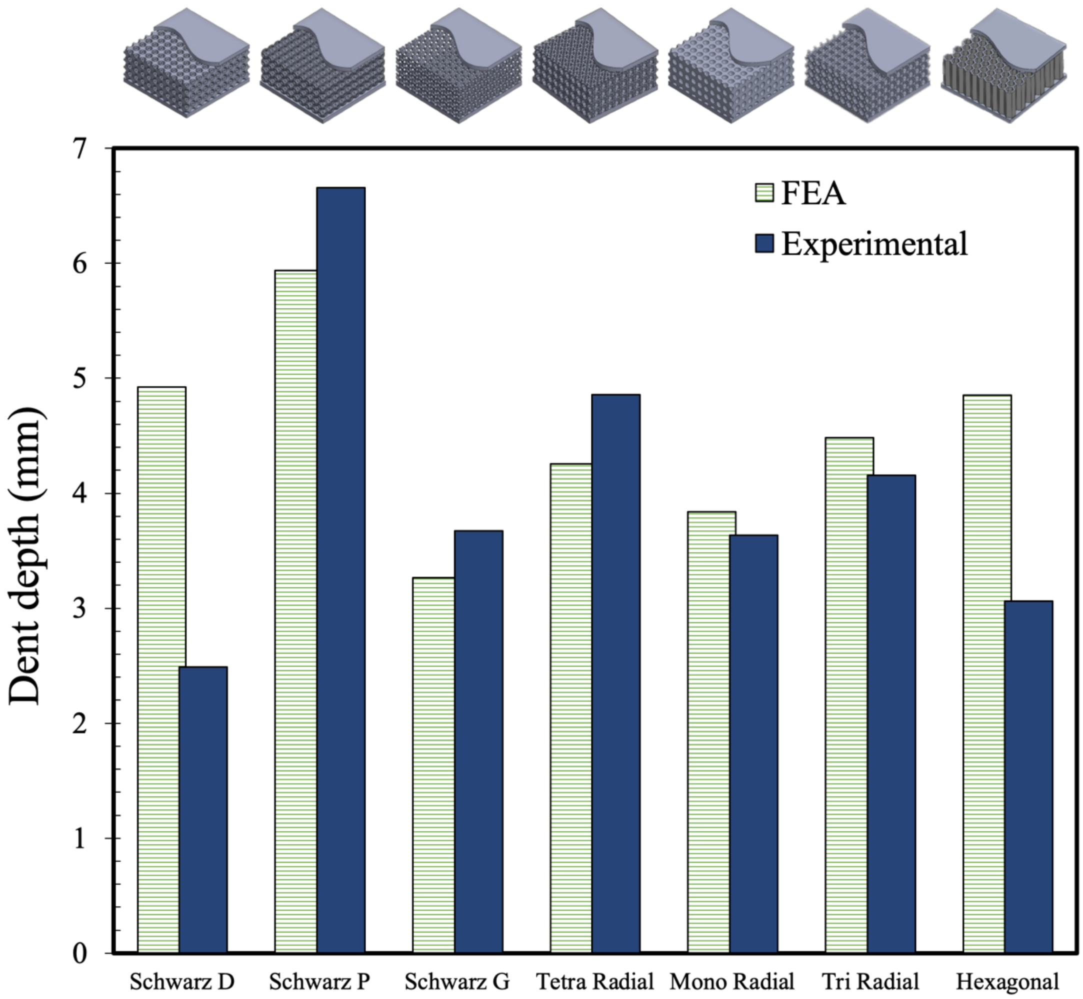

Figure 4.17. Analysis of the investigated sandwich panels: dent depth.

Importantly, this pattern of larger deformation and reduced contact forces after the second panel continues with the bioinspired Panel 4 and Panel 6, as previously discussed. These two panels replicate the behavior of Panel 2 in subsequent phases, affirming the consistent mechanical response intrinsic to this specific subset of designs. These comparative analyses underscore the unique mechanical responses and energy absorption capabilities demonstrated by the assessed sandwich panels, accentuating the profound impact of varying core topologies on their overall performance.

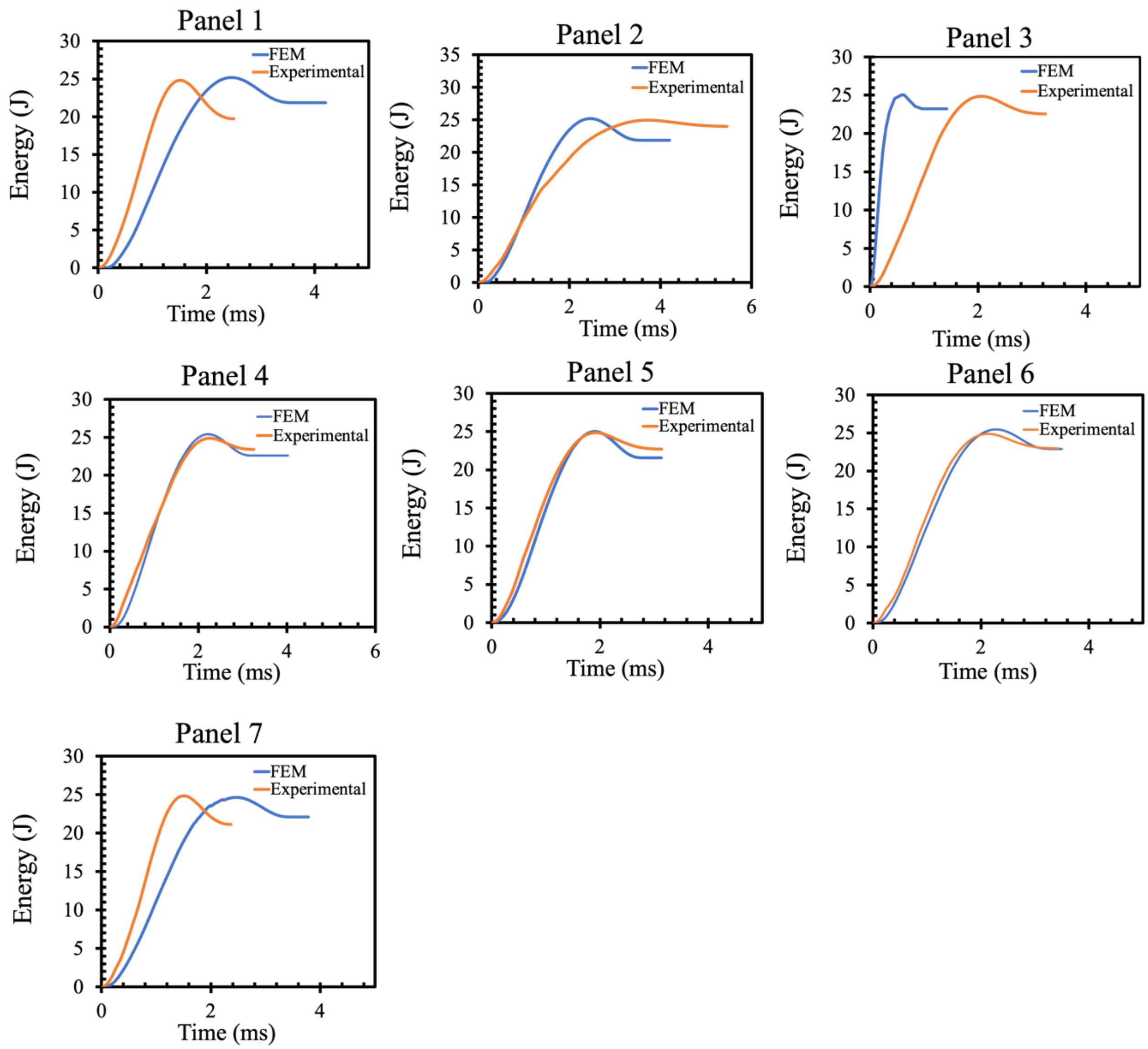

Figure 4.18. Energy-time history of alternative cell topology.

In the following, it's essential to highlight that the cumulative area beneath the complete force-displacement curve serves as a representation of the energy absorption potential inherent in a sandwich panel subjected to impact loading. As depicted in Figure 4.18, both experimental and numerical (finite element) results are presented, offering an insightful view of the energy-time progression across different cellular topologies. An impressive consensus emerges between the outcomes of experimental tests and numerical analyses. The energy absorption-time history graphically displays the quantities of absorbed and returned (released) energies during the impact test. Absorbed energy primarily dissipates through various failure mechanisms like delamination and cracking [65], while released energy signifies the elastic energy associated with reversible deformations and subsequent recovery within the panel. In this context, the evaluation of energy performance hinges on the ratio of absorbed energy to the maximum impact energy [66], thus providing a comprehensive measure of the panel's effectiveness in redistributing incoming energies while enduring dynamic loads.

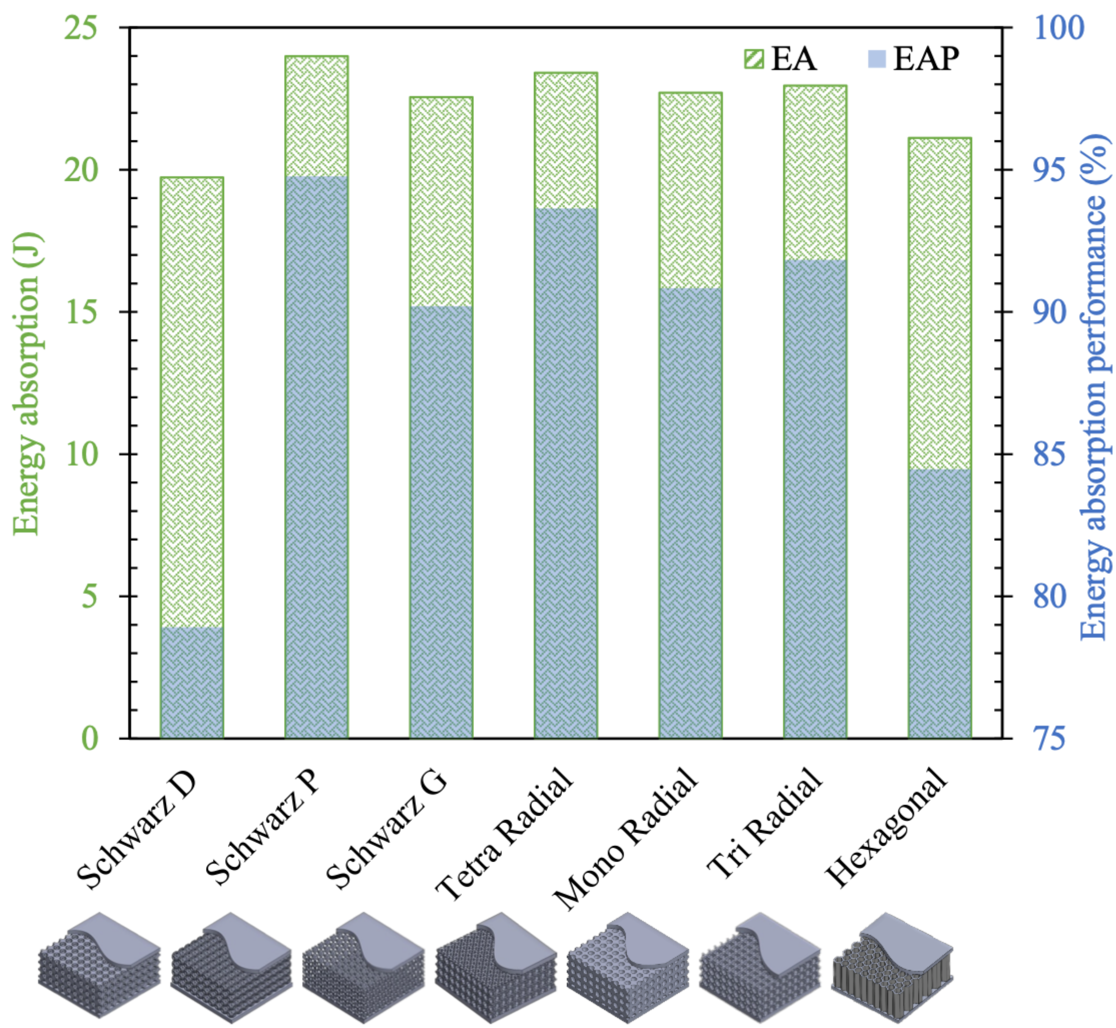

Figure 4.19. Comparison of the energy absorption of the sandwich panels of alternative cell topology derived from the experimental test. EA: Energy absorption, EAP: Energy absorption performance.

Moreover, it is crucial to recognize that the Finite Element Method (FEM) outcomes exhibit discrepancies when compared with the experimental data. This incongruity can be attributed to the nature of FEA results, which primarily rely on elastic stress-strain relations and do not encompass plasticity. This disparity highlights the need for careful consideration of both datasets, acknowledging their respective strengths and limitations. Additionally, Figure 4.19 serves as a visual representation of the energy absorption capabilities observed in seven distinct sandwich panels. These panels are distinguished by their diverse core topologies, encompassing Schwarz D, Schwarz P, Schwarz G, Tetra Radial, Mono Radial, Tri Radial, and Hexagonal designs. The comprehensive experimental impact assessments conducted on these panels offer valuable insights into their unique abilities for dissipating energy and sustaining loads across a spectrum of engineering applications. This analysis underscores the versatility and potential advantages of these various core topologies in practical engineering contexts.

As previously indicated, Schwarz P core topology (panel 2) exhibits a notable advantage in terms of energy absorption compared to the other scrutinized core topologies, however the panel with bioinspired design exhibits the amazing behaviour in the second spot. This superiority in energy absorption becomes evident when considering the energy-time progression represented in Figure 4.19 Except for Schwarz D core (panel 1) the remaining examined sandwich panels demonstrate a slightly enhanced energy absorption capacity when compared with the hexagonal sandwich panels. This observation underscores a tangible enhancement in the energy absorption capabilities of the investigated sandwich panels relative to those of the hexagonal counterpart. Furthermore, it is noteworthy to underscore that the Schwarz P core, as embodied in panel 2, emerges as the preferred core configuration for the architected sandwich panel in terms of energy absorption, specifically under the stipulated impact energy conditions. A discernible improvement of 10% in energy absorption performance is ascertained during experimental assessments, with the utilization of Schwarz P cores for the architected sandwich panels, in comparison to those equipped with the hexagonal cores. This performance boost reaffirms the advantageous nature of Schwarz P cores in enhancing the energy absorption capability of the architected sandwich panels within the specified impact energy context.

4.3 Effects of core topology on multi-hit performance

In this section, an in-depth exploration is undertaken to examine how the core topology influences the multi-hit behavior and energy absorption capabilities of 3D-printed sandwich panels. This includes panels with a variety of core types such as TPMS, novel closed-cell foam, and hexagonal structures. It's essential to note that all these panels share a consistent relative density of 40%, and they undergo a rigorous series of multi-hit low-velocity impacts, each with an energy magnitude of 25 J. Figure 4.20 draws attention to a noticeable increase in displacement at maximum load during the second impact. This dynamic behavior implies that the panels are more susceptible to impactor penetration during subsequent impacts.

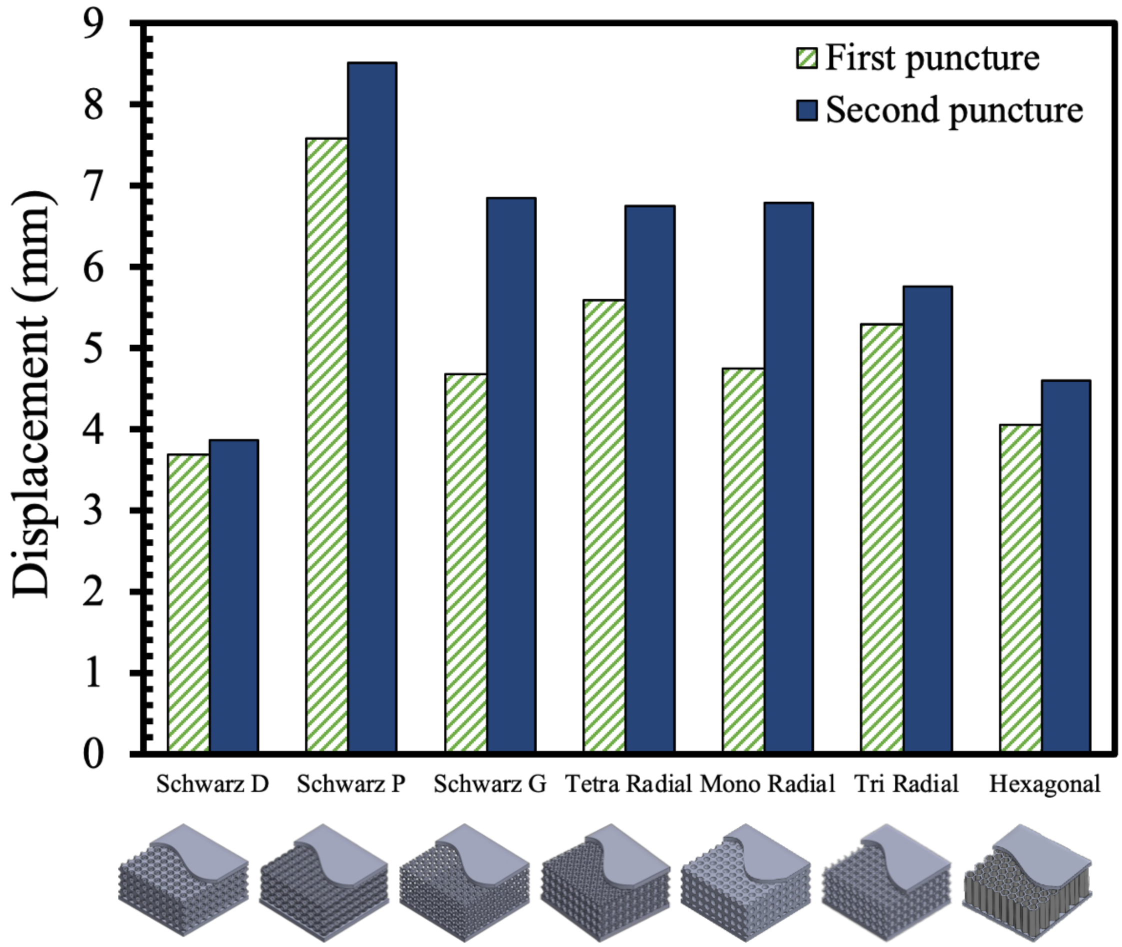

Figure 4.20. Analysis of mechanical properties obtained from the first and second hits of impact experimental tests: Displacement.

However, Figure 4.21 tells a different story, revealing a reduction in the maximum load during the second impact. This suggests that the resistance encountered by the impactor diminishes as it traverses the panels during successive impacts. This conflicting behavior underscores the complex.

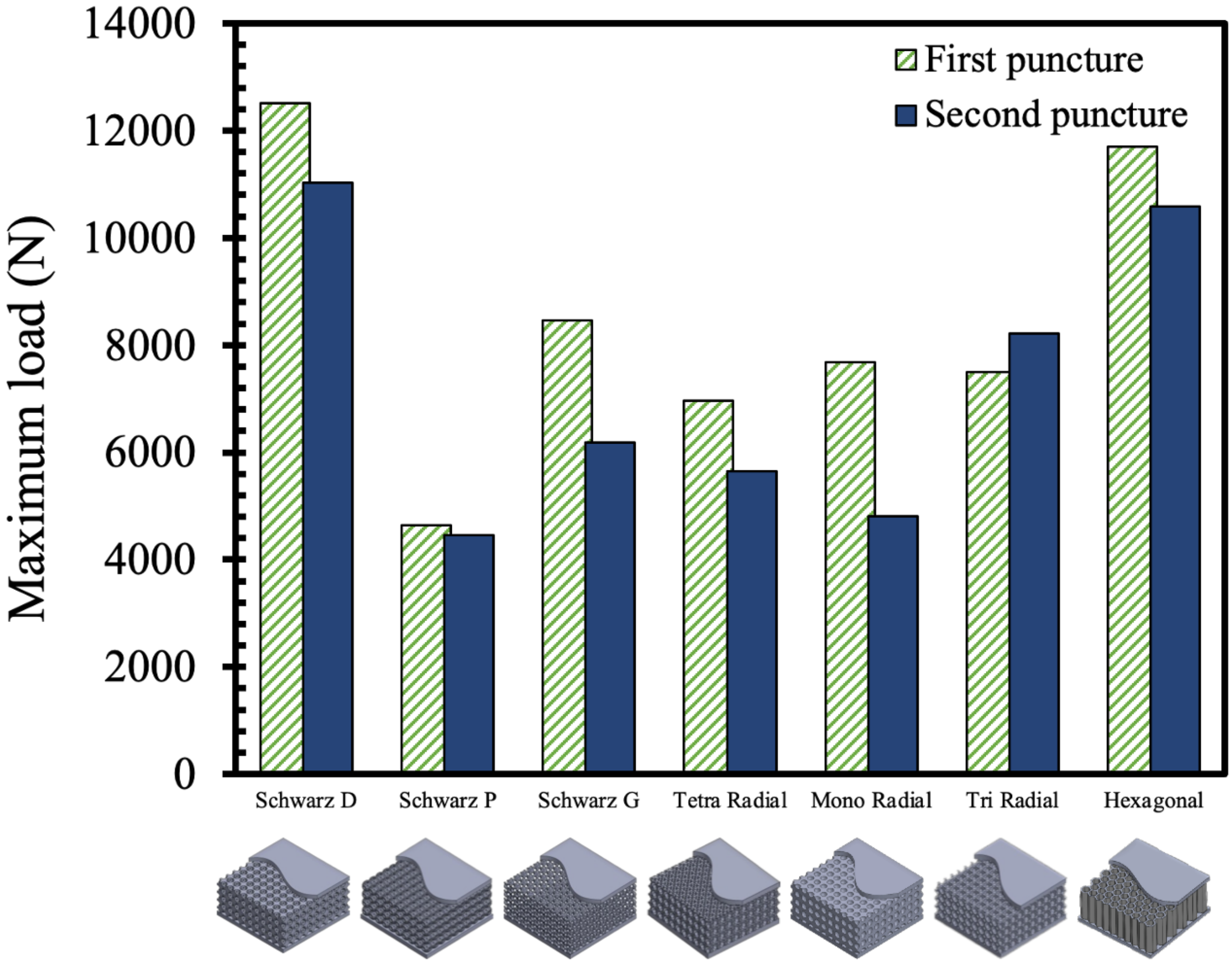

Figure 4.21. Analysis of mechanical properties obtained from the first and second hits of impact experimental tests: Maximum load.

Furthermore, Figure 4.22 provides a compelling visual representation of the development in dent depth for these 3D-printed sandwich panels. A substantial surge, ranging from 10.5% to 75%, in dent depth is observed during the second impact. This dramatic increase in dent depth serves as a clear indication of the damage sustained by the panels during the initial impact, subsequently compromising their ability to absorb energy effectively. This observation underscores the lasting effects of the initial impact on the structural integrity of the panels.

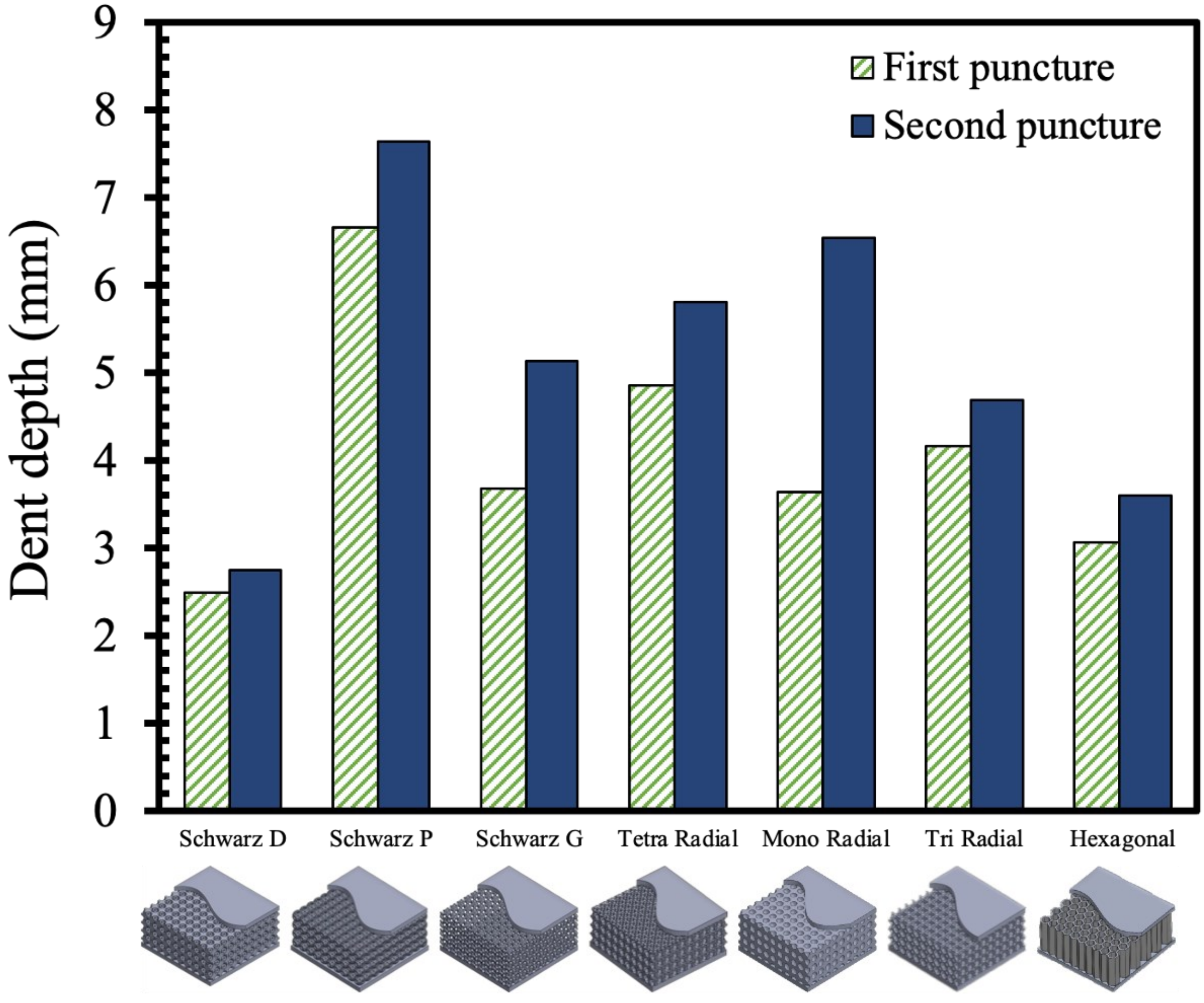

Figure 4.22. Analysis of mechanical properties obtained from the first and second hits of impact experimental tests: Dent depts.

Additionally, Figure 4.23 is instrumental in our understanding of how these panels respond to dynamic impacts and varying contact forces. What's intriguing here is the remarkable consistency in the energy absorption capacity of the panels, despite the dynamic nature of the impacts and the variances in contact forces. This stability in energy absorption aligns with our expectations, as a reduction was anticipated in contact force across all panels due to the successive impacts. This data reassures us about the panels' ability to consistently perform in multi-hit scenarios.

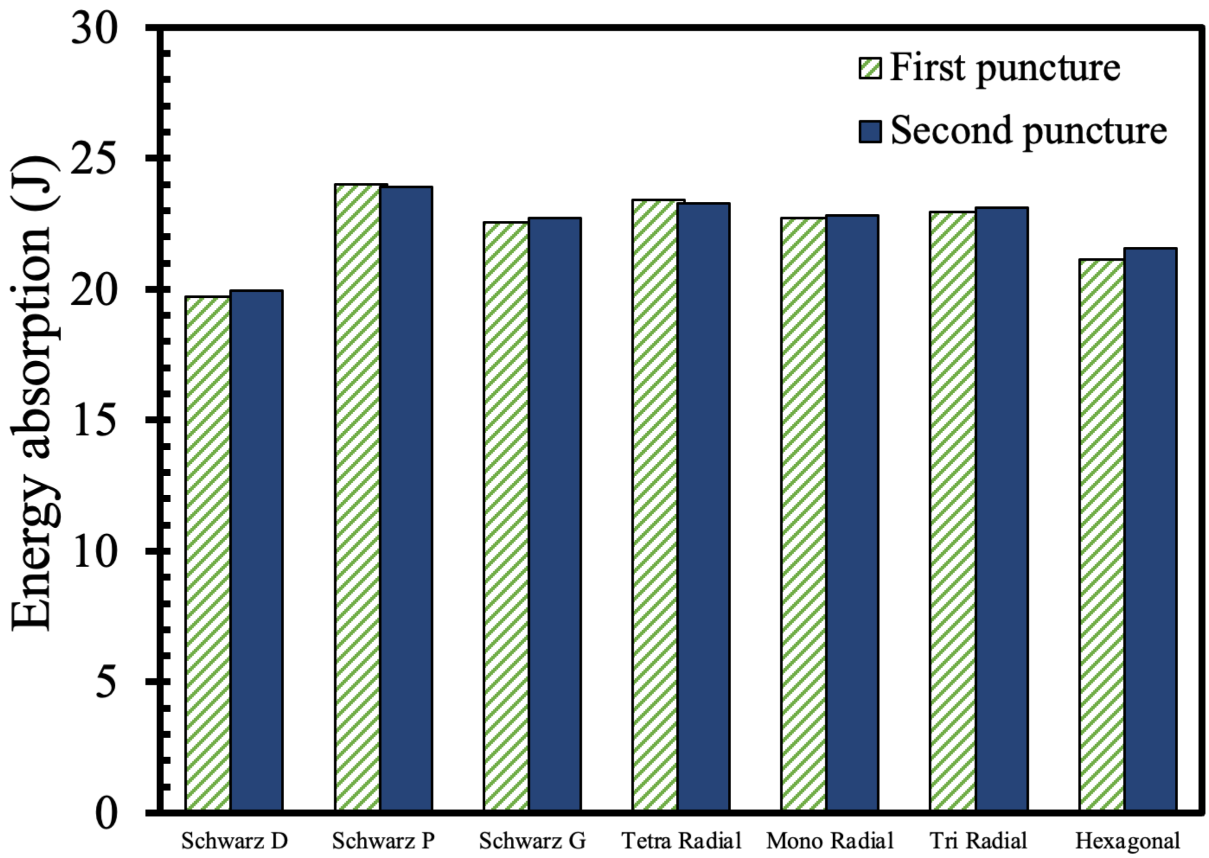

Figure 4.23. Analysis of mechanical properties obtained from the first and second hits of impact experimental tests: Energy absorption.

This visual documentation underscores the panels' susceptibility to failure mechanisms like crack propagation and delamination, shedding light on the structural challenges they face in multi-hit scenarios. The outcomes of our investigation unveil a robust dependency of the mechanical properties on several key factors, namely the core geometry, relative density, and the distribution of cell thickness. Satisfying congruence has been established between the results obtained through finite element simulations and the empirical data derived from experiments. This harmonious alignment serves to strengthen the credibility of our findings.

Among the pivotal findings, it is evident that the core geometry plays a pivotal role in determining the mechanical attributes of these panels. The results emphasize that, for panels sharing the same relative density, the bioinspired natural structures proposed in this study stand as formidable contenders when compared to traditional core structures, especially in terms of strength, stiffness, and energy absorption. This holds promise for a range of applications where structural integrity and load-bearing capacity are paramount. Beyond their mechanical prowess, these bioinspired panels exhibit additional merits in terms of mass production, cost-efficiency, structural robustness, and dimensional adaptability. These advantages reinforce their appeal for various engineering contexts, making them an enticing prospect for future applications in the field.

4.4 Comprehensive Analysis

Table 4 presents a comprehensive overview and the comparison of the energy performance during the 1st and 2nd impacts of the examined sandwich panels. A sandwich panel with octet core topology, recognized as the top-performing structure in terms of energy absorption [23], has been incorporated into this analysis. As previously noted, the results reveal that exceptional performance is demonstrated by sandwich panels that utilize Schwarz P and Tetra Radial core topologies. Their energy absorption performances, when compared to other panels within the study, show remarkable developments of 96% and 94%, respectively. When these high-performing panels are compared with the sandwich panels identical in size but featuring the Octet core geometry [23], which achieves a commendable 90% energy absorption performance, a clear trend is observed. This comparison highlights a noticeable improvement in the mechanical behavior of panels characterized by the optimized core geometries, particularly in the context of energy absorption.

Table 4. Overview and comparison of the energy absorption performance.

Core topology		Energy performance (%)	
Panel No.	Unit cell	1st puncture	2nd puncture
1	Schwarz D	78.92	79.84
2	Schwarz P	95.97	95.56
3	Schwarz G	90.02	90.82
4	Tetra Radial	93.63	93.13
5	Mono Radial	90.83	91.31
6	Tri Radial	91.83	92.48
7	Hexagonal	84.47	86.19
8	Octet [20]	90.13	88.91

The multifaceted nature of the study's findings warrants an in-depth discussion to provide a holistic view of the research outcomes. Several key aspects have been evaluated, including the consistency between numerical simulations and experimental results, the impact of core topology on energy absorption, and the multi-hit performance of the 3D-printed sandwich panels.

Consistency between numerical and experimental results: Our research establishes a remarkable consistency between the force-displacement curves derived from numerical simulations (FEA) and those obtained through experimental tests. For displacement ranges up to the yielding of sandwich panels, the correspondence between these two approaches is striking. This synchronization underscores the validity of employing numerical analysis to predict mechanical performance accurately. However, it is crucial to note that as displacement increases beyond the yielding point, discrepancies emerge due to the use of an elastic-perfectly plastic constitutive law in FEA. This law introduces deviations, particularly when deformation exceeds the elastic threshold, resulting in nuanced distinctions in the panels' behavior under load.

Impact of core topology on energy absorption: An integral part of our study involves assessing the impact of various core topologies on energy absorption capabilities. The results showcase distinct trends in energy absorption performance, with Tetra Radial and Schwarz P core topologies demonstrating superior energy absorption (up to 11% and 16%, respectively, for the 1st impact) and stiffness (up to 42% and 43%, respectively, for the 1st impact) when compared to the honeycomb structure. This highlights the critical role that core topology plays in shaping the mechanical response of the panels under impact conditions.

Multi-hit performance: Our investigation extends to evaluating the multi-hit performance of the 3D-printed sandwich panels. Results reveal that displacement at maximum load increases during the second impact, indicating enhanced impactor penetration through the panels. This is accompanied by a reduction in maximum load for the second impact, signifying decreased resistance faced by the impactor. Moreover, there's a notable increase in the depth of the dent (10.5% to 75%) during the second impact. It's evident that these dynamic impacts compromise the energy absorption capacity of the panels and contribute to failure mechanisms such as crack propagation and delamination.

Discussion synthesis: In synthesis, this comprehensive discussion underscores the multifaceted nature of the research outcomes. The consistency between numerical simulations and experimental results highlights the potential of numerical analysis for predicting panel behavior within the elastic threshold. The substantial impact of core topology on energy absorption is evident, with Tetra Radial and Schwarz P core topologies emerging as highly promising options. These results open new possibilities for engineering applications requiring enhanced energy absorption and stiffness. The multi-hit performance evaluation accentuates the panels' susceptibility to dynamic impacts and their associated failure mechanisms. This discussion reinforces the significance of the core topology in shaping the panels' overall mechanical response.

These findings underscore the critical role played by core topology in determining the energy absorption capabilities of sandwich panels. As potential directions for future development in this investigation are explored, it becomes apparent that the design and selection of core geometry exert a direct and substantial influence on the overall performance of sandwich structures. This insight establishes a robust foundation for forthcoming research endeavors, offering valuable guidance for the advancement of high-performance sandwich panel designs, the optimization of their mechanical attributes, and the enhancement of energy absorption capabilities.

CHAPTER 5 : CONCLUSION, CONTRIBUTIONS, AND FUTURE WORKS

This study has been a thorough exploration into the intricate interplay between various core architectures and the mechanical performance of 3D-printed sandwich panels. By seamlessly integrating numerical analysis with dynamic experimental tests, our study has unearthed a wealth of valuable insights that significantly contribute to the design, development, and application of these pioneering materials.

Key findings: Our in-depth investigations have unveiled several pivotal findings that underscore the profound influence of core topology on mechanical behavior:

- The core architecture is a decisive factor in determining failure mechanisms and energy absorption capabilities, as evident in the clear trends reflected in force-displacement curves. Force-displacement curves are graphs that show how the contact force and the deformation of a sandwich panel vary during an impact event. The shape and slope of these curves can reveal important information about the mechanical behavior of sandwich panels with different core topologies under low-velocity impact loading. Some of the aspects that can be inferred from these curves are:
  - The load-carrying capacity, which is the maximum contact force that a sandwich panel can withstand before failure.
  - The stiffness, which is the resistance of a sandwich panel to deformation under a given contact force.
  - The energy absorption, which is the amount of impact energy that a sandwich panel can dissipate through deformation and damage.
  - The deformation resilience, which is the ability of a sandwich panel to recover its original shape and size after an impact event.

5.1. Contributions

Panels featuring distinct core designs exhibited unique mechanical behaviors:

- The Schwarz D core demonstrates exceptional load-carrying capacity and stiffness. The Schwarz D core is a 3D cellular structure that has a diamond-like shape and pattern. This core has high connectivity and symmetry, which means that it has many nodes where the cell walls meet and that it has the same shape and orientation in all directions. These features make the Schwarz D core very rigid and strong, as it can distribute and resist stress and strain uniformly and efficiently throughout the structure. As a result, the sandwich panels with Schwarz D cores have high load-carrying capacity and stiffness, as shown by the high peak force and low deformation in their force-displacement curves.
- The Schwarz P core excels in energy absorption and deformation resilience during impact. The Schwarz P core is a 3D cellular structure that has a primitive-like shape and pattern. This core has low connectivity and symmetry, which means that it has few nodes where the cell walls meet and that it has different shapes and orientations in different directions. These features make the Schwarz P core very flexible and ductile, as it can deform and absorb stress and strain locally and non-uniformly throughout the structure. As a result, the sandwich panels with Schwarz P cores have high energy absorption and deformation resilience, as shown by the large area under the curve and high recovery ratio in their force-displacement curves.
- Bioinspired cores, such as Tetra Radial and Tri Radial, exhibit intriguing parallels to Schwarz P cores, marked by increased deformations and decreased contact forces. Bioinspired cores are 3D cellular structures that mimic the shapes and patterns found in nature, such as plants or animals. Some examples of bioinspired cores are Tetra Radial and Tri Radial, which have tetrahedral and triangular shapes and patterns, respectively. These cores have moderate connectivity and symmetry, which means that they have some nodes where the cell walls meet and that they have similar but not identical shapes and orientations in different directions. These features make the bioinspired cores moderately flexible and ductile, as they can deform and absorb stress and strain partially and variably throughout the structure. As a result, the sandwich panels with bioinspired cores have

moderate energy absorption and deformation resilience, as shown by the intermediate area under the curve and recovery ratio in their force-displacement curves. However, these cores also show some similarities to Schwarz P cores, such as increased deformations and decreased contact forces compared to Schwarz D cores. This suggests that bioinspired cores may have some advantages over conventional cores in terms of impact performance.

Multi-hit performance: The investigation extended to multi-hit scenarios, revealing nuanced aspects of the panels' response to successive impacts. Multi-hit scenarios are situations where sandwich panels are subjected to more than one impact event in the same or different locations. These scenarios can simulate the repeated impacts that sandwich panels may encounter during their service life, such as in military or aerospace vehicles. The response of sandwich panels to multi-hit scenarios can provide information about their residual strength, stiffness, energy absorption, and damage tolerance after the first impact.:

- Second impacts reveal heightened impactor penetration, reduced resistance, and complex mechanical responses. The second impacts are the impacts that occur after the first impacts in the same or different locations on the sandwich panels. The second impacts can cause more damage and deformation to the sandwich panels than the first impacts, as the sandwich panels have already lost some of their structural integrity and functionality after the first impacts. The second impacts can result in increased impactor penetration, which means that the impactor can go deeper into the sandwich panel and cause more damage to the face sheets and the core. The second impacts can also result in reduced resistance, which means that the sandwich panel can offer less force and stiffness to oppose the impactor and prevent further deformation and damage. The second impacts can also result in complex mechanical responses, which means that the sandwich panel can show different and unpredictable behaviors depending on the location, magnitude, and direction of the second impacts, as well as the damage state of the sandwich panel after the first impacts.
- Encouragingly, energy absorption performance remains consistent across panels, even in the face of variations in contact forces and deformations. The energy absorption performance is the ability of sandwich panels to dissipate impact energy through deformation and damage. This is an important aspect for sandwich panels under impact

loading, as it can reduce the amount of impact energy that is transmitted to other parts of the structure or to the occupants inside. The energy absorption performance can be measured by calculating the area under the force-displacement curve, which represents the work done by the impactor on the sandwich panel during an impact event. The investigation showed that the energy absorption performance of sandwich panels with different core topologies remained consistent across panels, even when they were subjected to second impacts that caused variations in contact forces and deformations. This means that sandwich panels with different core topologies can still dissipate a similar amount of impact energy after being damaged by the first impacts, which is a desirable property for sandwich panels under multi-hit scenarios.

- The panels' susceptibility to failure mechanisms, particularly along 3D printing directions, became apparent. The failure mechanisms are how damage initiates and propagates in sandwich panels under impact loading, such as delamination, core crushing, face sheet debonding, or perforation. The failure mechanisms can affect not only the energy absorption capacity but also the residual strength and stiffness of sandwich panels after impact loading. The investigation showed that sandwich panels with different core topologies were susceptible to different failure mechanisms depending on their core architecture and 3D printing directions. 3D printing directions are the directions along which the material is deposited during additive manufacturing (AM), also known as 3D printing. AM is a method of fabricating complex parts using various materials by adding material layer by layer according to a digital model. AM can create novel structures with desired properties and characteristics, but it can also introduce anisotropy and heterogeneity in the material properties and behavior along different directions. The investigation showed that some failure mechanisms were more likely to occur along certain 3D printing directions than others, which can affect the impact response and damage of sandwich panels with different core topologies under multi-hit scenarios.

Mechanical properties and sustainability: The study affirms that mechanical properties are inextricably linked to core topology, relative density, and cell thickness distribution. Mechanical properties are the characteristics of a material or a structure that determine its behavior under various forces and conditions, such as stress, strain, deformation, or failure. Core topology is the shape and pattern of the cellular structure that forms the core layer of a sandwich panel. Relative density is the ratio of the density of a cellular structure to the density of a solid material with the same composition. Cell thickness distribution is the variation of the thickness of the cell walls in a cellular structure. These factors affect the mechanical properties of sandwich panels with different core topologies under low-velocity impact loading, such as stiffness, strength, energy absorption, failure modes, and multi-hit capability. Satisfactory agreement between finite element results and experimental data underscores the robustness of our approach.

- Satisfactory agreement between finite element results and experimental data underscores the robustness of our approach. Finite element results are the outcomes of numerical modeling using finite element analysis (FEA), which is a method of simulating the mechanical behavior of various structures under different loading conditions using numerical methods. Experimental data are the outcomes of experimental tests using low-velocity impact testing, which is a method of simulating the impact events that sandwich panels may encounter during their service life using a drop-weight tower. The study showed that the finite element results and experimental data were consistent and comparable in terms of the force-displacement curves, which are graphs that show how the contact force and the deformation of a sandwich panel vary during an impact event. The satisfactory agreement between finite element results and experimental data indicates that our approach of combining numerical modeling and experimental testing is reliable and accurate in predicting and understanding the impact response and damage of sandwich panels with different core topologies.

- Bioinspired structures emerge as formidable competitors to traditional cores, boasting superior strength, stiffness, and energy absorption capabilities. Bioinspired structures are 3D cellular structures that mimic the shapes and patterns found in nature, such as plants or animals. Some examples of bioinspired structures are Tetra Radial and Tri Radial, which have tetrahedral and triangular shapes and patterns, respectively. Traditional cores are 3D cellular structures that have regular and simple shapes and patterns, such as honeycombs or lattices. The study showed that bioinspired structures had better mechanical properties than traditional cores under low-velocity impact loading, such as higher strength, higher stiffness, and higher energy absorption. Strength is the ability of a material or a structure to resist failure under a given force. Stiffness is the resistance of a material or a structure to deformation under a given force. Energy absorption is the amount of impact energy that a material or a structure can dissipate through deformation and damage. These properties are important for sandwich panels under impact loading, as they can improve their performance and reliability.

- Furthermore, they offer strategic advantages in terms of mass production, cost-effectiveness, structural robustness, and dimensional flexibility. Bioinspired structures also have other benefits over traditional cores in terms of manufacturing, design, and application. Mass production is the ability to produce large quantities of a product in a short time and at a low cost. Cost-effectiveness is the ability to provide good value for money by achieving the desired results at a reasonable cost. Structural robustness is the ability to maintain functionality and integrity under various conditions and uncertainties. Dimensional flexibility is the ability to change or adjust the size or shape of a product according to different needs or preferences. The study showed that bioinspired structures can be easily and cheaply fabricated using additive manufacturing (AM), also known as 3D printing, which is a method of creating complex parts using various materials by adding material layer by layer according to a digital model. The study also showed that bioinspired structures can be more resilient and adaptable than traditional cores under different loading scenarios and environmental factors, such as temperature or humidity.

5.2. Future works

This research provides a solid basis for future work, but it also identifies areas that need more investigation: Long-term Durability and Environmental Impacts:

Long-term Durability and Environmental Impacts: The study does not delve into the long-term durability and environmental impacts of these materials, which is essential for understanding their overall sustainability. To address this, future research should encompass:

- Extended studies that evaluate the durability and environmental sustainability of these advanced materials. These studies should measure how the materials perform under various stress and strain conditions, such as compression, tension, bending, and shear. They should also assess how the materials degrade over time and how they interact with the surrounding environment, such as air, water, soil, and biota.

- Exploration of the effects of extended use and adaptability to varying environmental conditions. These effects include how the materials respond to changes in temperature, humidity, pressure, and radiation. They also include how the materials cope with wear and tear, corrosion, fatigue, and damage. Furthermore, they include how the materials can be modified or repaired to extend their lifespan and functionality.
- Investigating sustainable end-of-life solutions, including recycling and repurposing. These solutions involve how the materials can be recovered and reused for other purposes, such as energy production, waste management, or construction. They also involve how the materials can be disposed of safely and responsibly, without harming the environment or human health.

Standardizing Testing Protocols: Standardization of testing protocols and performance metrics is paramount to establish a unified framework for:

1. Assessing the mechanical attributes and performance of the architected 3D-printed sandwich panels. These attributes include stiffness, strength, toughness, ductility, and fracture resistance. These performance metrics include load-bearing capacity, energy absorption, impact resistance, and vibration damping. The testing protocols should specify the methods, equipment, and conditions for conducting these measurements and evaluations.
2. Facilitating comparisons between different core topologies and material compositions. These comparisons should consider the effects of varying the geometry, size, density, and orientation of the core cells. They should also consider the effects of changing the material type, composition, and properties of the core and face sheets. The testing protocols should provide the criteria, benchmarks, and indicators for making these comparisons.

This multifaceted approach aims to address the current research’s limitations and guide future investigations toward a more comprehensive understanding of these innovative structures. This approach involves:

1. Conducting long-term studies on the durability and environmental impacts of these materials, such as how they perform under various stress and strain conditions, how they degrade over time and interact with the surrounding environment, and how they can be recovered and reused for other purposes.
2. Exploring the effects of extended use and adaptability to varying environmental conditions, such as how the materials respond to changes in temperature, humidity, pressure, and radiation, how they cope with wear and tear, corrosion, fatigue, and damage, and how they can be modified or repaired to extend their lifespan and functionality.
3. Examining sustainable end-of-life solutions, such as recycling and reusing, for these materials, such as how they can be disposed of safely and responsibly, without harming the environment or human health.
4. Standardizing testing protocols and performance metrics for these materials, such as specifying the methods, equipment, and conditions for measuring and evaluating their mechanical properties and performance, such as stiffness, strength, toughness, ductility, fracture resistance, load-bearing capacity, energy absorption, impact resistance, and vibration damping.
5. Facilitating comparisons between different core topologies and material compositions for these materials, such as considering the effects of varying the geometry, size, density, and orientation of the core cells, and changing the material type, composition, and properties of the core and face sheets.
6. This multifaceted approach aims to address the current research's limitations and guide future investigations toward a more comprehensive understanding of these innovative structures. In conclusion, this comprehensive study not only lays the foundation for a new era of sandwich panel design, characterized by customized core topologies but also highlights the promising potential of developing advanced materials. These materials offer elevated mechanical attributes and amplified energy absorption capabilities, positioning them for a myriad of applications. However, a

candid acknowledgment of the study's limitations and an unwavering commitment to sustainability and long-term viability are imperative for the continued evolution of this groundbreaking research in materials engineering.

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