

**T.C.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL**

**FLEXURAL BEHAVIOR OF SANDWICH BEAMS WITH
AUXETIC CORE STRUCTURES**



EMRE TAYYİP TAN

**A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF MECHANICAL ENGINEERING**

ADVISOR: ASSOC. PROF. DR. FATİH USTA

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LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

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*To my wife, for her endless
support, patience, and
encouragement throughout this
journey...*

ABSTRACT

The sandwich beams contributed significantly to energy absorption, as did the auxetic materials. This study presents an experimental and numerical investigation of re-entrant auxetic cores made through the FDM process to enhance the flexural bending response of sandwich beams and their energy absorption capacity. Auxetic cores were designed and fabricated with cell wall thicknesses that vary from top to bottom, with four uniform thicknesses of 0.5, 0.75, 1.0, and 1.25 mm. All sandwich beams featured 0.5 mm thick Al1050 face sheets and were bonded with epoxy adhesive.

Three-point bending tests were performed following ASTM C393-00 standards. The results showed that the use of auxetic cores led to improvements in both the load-carrying capacity and the energy absorption capability of the sandwich beams. In particular, designs with graded cell wall thickness enabled a more uniform load distribution, which helped delay localized damage and resulted in higher energy absorption when compared with uniform-thickness configurations. In addition to these specimens, a foam-filled configuration with a uniform cell thickness of 0.75 mm was manufactured and tested in order to examine the influence of core filling on flexural response and energy dissipation. The foam-filled specimen exhibited a more constrained deformation mode and demonstrated a higher energy absorption capacity than its unfilled counterpart, indicating that foam filling can be considered an effective approach for further enhancing the structural performance.

Numerical analyses were carried out using structured three-dimensional and two-dimensional finite element meshes, and the corresponding models were solved in Abaqus to replicate the three-point bending test conditions. The numerical outcomes showed good agreement with the experimental load–deflection responses, with deviations remaining within acceptable limits. Furthermore, the predicted stress distributions and strain fields were consistent with the deformation mechanisms observed during the experiments. For specimens with graded cell wall thickness, plastic deformation and damage were distributed over a wider region, which contributed to delayed fracture and improved energy dissipation.

The overall findings highlight that both cell geometry and variations in wall thickness play a critical role in determining the mechanical performance of sandwich beams. In this context, the use of wall thickness gradients in re-entrant auxetic cores was found to be an effective approach for improving bending strength as well as energy absorption capacity. The results obtained from the foam-filled configuration further demonstrate that combining auxetic core designs with internal filling provides an alternative means of controlling deformation modes and enhancing energy dissipation during bending. For future studies, different filling materials and density levels, together with multi-material core designs, may be investigated to achieve further optimization of the bending behavior of auxetic sandwich beam structures.

Keywords: Sandwich beam, Auxetic core structure, Re-entrant cores, Flexural bending behavior.

ÖZET

Sandviç kiriş yapıları ve oksetik malzemeler, enerji yutma konusundaki önemli katkıları nedeniyle tanınmaktadır. Bu çalışma, deneysel ve sayısal analizler yoluyla, FDM yöntemiyle üretilen re-entrant oksetik çekirdeklerin, sandviç kirişlerin hem eğilme davranışını hem de enerji yutma kapasitesini artırma potansiyelini ortaya koymaktadır. Oksetik çekirdekler, üstten alta doğru artan ve azalan gradyanlara sahip hücre duvar kalınlığı konfigürasyonları ile birlikte dört farklı üniform kalınlık tasarımı (0.5, 0.75, 1.0 ve 1.25 mm) kullanılarak tasarlanmış ve üretilmiştir. Tüm sandviç kirişler, 0.5 mm kalınlığında Al1050 yüzey levhaları ve epoksi yapıştırıcı kullanılarak monte edilmiştir.

Üç nokta eğilme deneyleri ASTM C393-00 standardına uygun olarak gerçekleştirilmiştir. Deneysel sonuçlar, oksetik çekirdek kullanımının sandviç kirişlerin hem yük taşıma kapasitesini hem de enerji yutma kapasitesini iyileştirdiğini göstermiştir. Gradyan kalınlık konfigürasyonları, yükü daha geniş bir bölgeye dağıtmış, yerel hasar başlangıcını geciktirmiş ve üniform kalınlıktaki tasarımlara kıyasla daha yüksek enerji yutma sergilemiştir. Doldurulmamış konfigürasyonlara ek olarak, çekirdek dolgusunun eğilme davranışı ve enerji sönümleme üzerindeki etkisini kısaca değerlendirmek amacıyla 0.75 mm üniform kalınlığa sahip çekirdeğin köpük dolgulu bir versiyonu da üretilmiş ve test edilmiştir. Köpük dolgulu numune, doldurulmamış muadiliyle karşılaştırıldığında daha kısıtlanmış bir deformasyon deseni ve artmış bir enerji yutma eğilimi sergilemiş olup, bu durum köpük dolgusunun yapısal performansı daha da iyileştirmek için tamamlayıcı bir strateji olma potansiyeline işaret etmektedir.

Sayısal analizler, yapılandırılmış 3B ve 2B ağ elemanları kullanılarak gerçekleştirilmiş ve sonlu eleman modelleri, deneysel üç nokta eğilme konfigürasyonunu yeniden üretmek amacıyla Abaqus yazılımında çözülmüştür. Sonlu eleman sonuçları, deneysel yük-sehim eğrileri ile kabul edilebilir sapmalarla iyi bir uyum göstermiştir. Tahmin edilen gerilme dağılımları ve birim şekil değiştirme alanları, deneysel olarak gözlemlenen deformasyon mekanizmalarıyla tutarlı bulunmuştur. Gradyan hücre duvarlarında plastik deformasyon ve ilerleyici hasar daha geniş bir bölgeye yayılmış olup, bu durum kırılmanın gecikmesine ve enerji sönümlemenin artmasına katkıda bulunmuştur.

Genel olarak, elde edilen bulgular sandviç kiriş performansında hücre geometrisi ve kalınlık dağılımının kritik rolünü vurgulamaktadır. Re-entrant oksetik çekirdeklerde hücre duvar kalınlığı gradyanları hem eğilme dayanımını hem de enerji yutma kapasitesini optimize etmek için etkili bir strateji olduğunu kanıtlamıştır. Ek olarak, köpük dolgulu değerlendirme, oksetik çekirdek topolojisinin iç dolgu ile birleştirilmesinin, eğilme yükleri altında deformasyon modlarını düzenlemek ve enerji sönümlemeyi artırmak için alternatif bir yol sağlayabileceğini göstermektedir. Gelecek çalışmalar, farklı dolgu malzemeleri ve yoğunluklarının incelenmesi ile birlikte, eğilme yükleri altında oksetik sandviç kirişlerin mekanik tepkisini daha da optimize etmek amacıyla çok malzemeli çekirdek uygulamalarının araştırılmasını içerebilir.

Anahtar Kelimeler: Sandviç kiriş, Oksetik çekirdek yapısı , Re-entrant çekirdek, Esnek eğilme davranışı.

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LIST OF SYMBOLS AND ABBREVIATIONS

ε	: Strain
σ	: Stress
3PB	: Three-point bending
F	: Force
AA1050	: Aluminum 1050 Alloy
CAD	: Computer-aided design
STL	: STL files for CAD models
FDM	: Fused Deposition Modeling
PLA	: Polylactic acid
PU	: Polyurethane (foam)
IE	: Internal Energy
KE	: Kinetic Energy
N	: Newton (load)
kg	: kilogram
J	: Joule (energy)
mm	: Milimeter

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1. INTRODUCTION

1.1 Overview and Problem Statement

Sandwich structures are multilayer composite systems consisting of thin, yet high-strength and stiff face sheets located on both outer surfaces, and a thick, low-density core layer positioned between these face sheets. Owing to this architecture, while the load-carrying capacity and flexural stiffness can be significantly increased, the total mass of the system can be kept low. Because of properties such as high energy-absorption capacity per unit weight, high specific stiffness, and high specific strength, sandwich structures are widely used as energy-absorbing, impact-resistant, and lightweight structures in many industrial fields such as automotive, aerospace, defense, biomedical, and robotics (Castanié et al., 2020; Francisco et al., 2023; Li et al., 2023; Tunay, 2024; Usta, 2024; Wang et al., 2023).

The main factors determining the performance of these structures can be summarized as the material properties (elastic modulus, yield strength, density, and similar) and geometric properties (thickness, cell size, cell shape, core height, and similar) of the face sheets and the core material. In particular, the topological parameters of the cellular core (e.g., cell-wall thickness, cell length, cell angle, porosity ratio) directly affect the load-transfer mechanism between the face sheets and the core, thereby governing the global bending, shear, and local buckling behaviors of sandwich beams (Zhao et al., 2021; Lu et al., 2023).

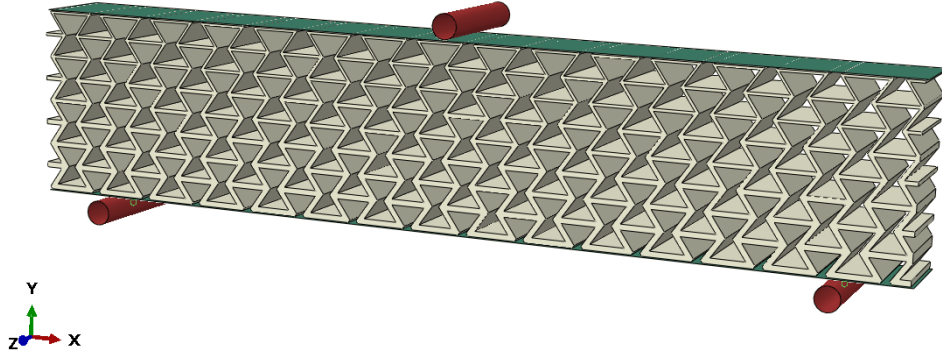


Figure 1.1: Schematic representation of a sandwich beam and the 3PB configuration.

In recent years, rapid developments in additive manufacturing technologies have enabled the precise fabrication of complex lattice- and metamaterial-based cores beyond conventional honeycomb or foam cores (Essassi et al., 2020; Tunay, 2024; Usta, 2024; Zeng et al., 2022; Zhao et al., 2021). In particular, polymer-based three-dimensional printing methods such as Fused Deposition Modeling (FDM) provide a design environment in which geometric complexity does not significantly increase manufacturing cost; thus, they make it possible to systematically investigate the effects of small-scale topological variations on large-scale mechanical behavior (Usta, 2024).

In this context, two main design strategies stand out in literature. The first is the use of different unit-cell configurations (re-entrant, chiral, arrowhead, star-shaped, etc.) as the core (Lu et al., 2023; Peng et al., 2022; Sengul et al., 2025; Usta, 2024). The second is to transform the core or the entire sandwich structure into a functionally graded (FG) structure; that is, to continuously or stepwise vary the material or geometric properties along the structure (Chen et al., 2024; Shirzad et al., 2024).

Auxetic materials, which constitute one of these design approaches, represent a special class of mechanical metamaterials that exhibit a negative Poisson's ratio. Because of this property, which is uncommon in nature, auxetic structures can simultaneously expand laterally and extend in the loading direction under tensile loading; under compressive loading, they can both contract laterally and shorten in the loading direction (Dutta et al., 2021; Sengul et al., 2025; Usta, 2024). This distinctive deformation behavior offers clear advantages over conventional materials across several mechanical performance criteria, including energy absorption, fracture toughness, indentation resistance, and dynamic response. These benefits originate

from the way the cellular architecture of auxetic structures evolves when subjected to external loading.

Under tensile loading, the outward rotation and opening of cell walls increase the effective cross-sectional area, reduce local stress concentrations, and geometrically enhance axial stiffness. In contrast, when exposed to compressive loading, re-entrant cells undergo a controlled inward folding mechanism. This deformation mode promotes a gradual and stable structural response rather than localized failure, thereby enabling key crashworthiness features such as high energy absorption and an extended plateau region in the load–displacement response (Essassi et al., 2020; Francisco et al., 2023).

The presence of a negative Poisson's ratio (NPR) also plays a critical role in governing damage evolution and crack propagation. Unlike conventional materials, auxetic structures tend to close crack tips rather than open them, which enhances fracture toughness and slows crack growth by lowering the stress intensity factor (K_{I1}) at critical locations. As a result, auxetic materials are particularly well suited for lightweight structural applications where high resistance to fracture is required. In addition, the lateral expansion exhibited by auxetic geometries under shear loading can reduce shear deformation, increase effective shear stiffness, and improve overall structural stability (Peng et al., 2022).

Auxetic materials also exhibit mechanical responses under dynamic loading that differ substantially from those of traditional cellular structures. The lateral expansion associated with NPR behavior contributes to increased dynamic stiffness, faster longitudinal wave propagation, and a more stable response under high-frequency excitation (Zeng et al., 2022; Wang et al., 2023). Moreover, the impact and blast resistance of re-entrant auxetic cores is significantly enhanced by the so-called sequential snap-through instability mechanism. This behavior allows energy to be dissipated in a controlled manner through successive instability events during high-velocity loading (Li et al., 2023; Yan et al., 2023).

Taking together, these mechanical characteristics enable auxetic structures to provide a range of engineering advantages at the macroscopic scale, including a high strength-to-weight ratio, large deformation capability, improved energy absorption, and

superior damage tolerance. Consequently, auxetic materials have attracted considerable attention in modern structural applications that require lightweight design combined with high strength and impact resistance. Among the various auxetic geometries reported in the literature, re-entrant, chiral, arrowhead, and star-shaped lattice configurations are the most extensively studied (Lu et al., 2023; Peng et al., 2022; Sengul et al., 2025; Usta, 2024). In particular, re-entrant lattice structures can be tailored by modifying topological parameters such as cell angle and wall thickness, allowing different instability modes and sequential snap-through behaviors to be achieved under both quasi-static bending and impact loading conditions, depending on the applied load level and strain rate (Li et al., 2023; Usta, 2024; Wang et al., 2023; Zhao et al., 2021). Owing to their high energy absorption capability, auxetic cores therefore represent promising candidates for use in sandwich beam structures.

Nevertheless, auxetic cores have certain limitations, particularly in terms of absolute stiffness and strength. In structures where re-entrant geometries are used alone, elastic stiffness and yield strength often remain limited due to the low relative density; this may restrict their use in applications requiring high load-carrying capacity (Lu et al., 2023; Sengul et al., 2025). Therefore, using auxetic lattices as the core layer within sandwich structures emerges as a hybrid approach that makes it possible to benefit simultaneously from the high stiffness and strength provided by the face sheets and the energy-absorption and impact-resistance features of the auxetic core (Lu et al., 2023; Usta, 2024).

Taking this hybrid concept further, the present thesis investigates in detail the effect of cell-wall thickness on the mechanical behavior of re-entrant auxetic-core sandwich beams. The main problem of the study is to compare the performance of auxetic cores with uniform (constant) wall thickness with functionally graded (FG) re-entrant cores in which the cell-wall thickness is varied stepwise along the beam height; thereby, the study aims to determine which design strategy is superior in terms of flexural behavior, energy-absorption capacity, and weight efficiency. In addition, to reveal structural differences with non-auxetic structures, beams with a foam-type core will also be investigated. To this end, both experimental three-point bending tests and finite element analyses will be conducted, and the results will be evaluated comparatively.

1.2 Importance and Usage of Sandwich Structures

Sandwich structures, in terms of their mechanical behavior, operate similarly to conventional I-section structural members. While face sheets with high elastic modulus and yield strength carry the applied bending moments and in-plane tensile/compressive loads, the low-density core material maintains the distance between the face sheets, carries shear stresses, and provides stability against buckling (Francisco et al., 2023; Lu et al., 2023; Zhao et al., 2021). This load sharing makes it possible to achieve much higher flexural stiffness and collapse load compared with a monolithic beam of the same weight (Castanié et al., 2020; Wang et al., 2023).

When the core thickness is increased, the distance between the face sheets also increases; this dramatically increases bending resistance by significantly raising the second moment of area of the cross-section. However, because the core generally has a porous or cellular topology, the added thickness does not cause a large mass increase. Thus, sandwich structures are highly advantageous in terms of specific stiffness and specific strength (Lu et al., 2023; Zhao et al., 2021). At the same time, owing to the porous structure of the core material, large plastic deformations can occur during impact or collision, and kinetic energy can be significantly distributed and dissipated (Essassi et al., 2020; Francisco et al., 2023; Li et al., 2023; Zeng et al., 2022). These characteristics make sandwich structures particularly suitable for use in critical safety-related components, including crash boxes, energy absorbers, and ballistic protection systems (Bao et al., 2022; Xiao et al., 2019; Yan et al., 2023).

Another important aspect that enhances the relevance of sandwich structures in engineering applications is their high level of design flexibility. Depending on the specific performance requirements, a wide range of material combinations and geometric configurations can be employed for both the face sheets and the core. For instance, aramid honeycomb cores are commonly combined with aluminum or carbon-fiber-reinforced plastic (CFRP) face sheets in aerospace applications (Castanié et al., 2020; Francisco et al., 2023). In contrast, steel, aluminum, and polymer-based core materials are more frequently adopted in automotive and railway structures (Li et al., 2022; Wang et al., 2023). In the biomedical field, the use of additively manufactured polymeric or biodegradable cores enables the development of lightweight and impact-resistant, implant-like structures (Essassi et al., 2020; Shirzad et al., 2024).

Previous studies have demonstrated that tailoring the core topology can lead to more pronounced improvements in the mechanical performance of sandwich structures than modifications to the face-sheet thickness or material alone. As an example, Li et al. (2022) investigated the bending behavior of sandwich structures incorporating aluminum honeycomb cores and examined the influence of face-sheet thickness, core height, and core topology on the observed failure mechanisms. They demonstrated that, in some loading scenarios, core topology can become one of the most important design parameters. Similarly, Bao et al. (2022) evaluated the mechanical and ballistic properties of hybrid carbon/aramid woven laminates and demonstrated that laminated composites have high potential in terms of energy dissipation and impact resistance.

Thanks to these superior features, sandwich structures are in the aerospace and space sector, in aircraft wings, fuselage panels, helicopter blades, and satellite supporting structures; in the automotive sector, in both load bearing and energy absorbing components such as chassis elements, crash boxes, hood and door panels; in maritime and offshore applications, in ship decks, hull panels, and wind-turbine blades; in construction and architectural applications, in façade panels, lightweight roof systems, and vibration-isolated floors; in sports equipment and protective gear (helmets, chest protectors, etc.). They are used across a very wide range of applications (Castanié et al., 2020; Francisco et al., 2023; Sengul et al., 2025; Wang et al., 2023; Zeng et al., 2022). This widespread application makes it important to examine sandwich structures in detail both theoretically and practically, and to develop next-generation core topologies.

1.3 Lattice Structures and Mechanical Metamaterials

Lattice structures can be defined as cellular architectures consisting of interconnected strut elements arranged periodically or semi-periodically in three-dimensional space (Zhao et al., 2021). Biological systems optimized for load bearing, such as spongy bone, trabecular structures, or plant stems, have inspired the design of lattice structures (Shirzad et al., 2024). These natural structures achieve both lightness and high strength by placing most of the material in locations that are effective for load carrying.

Compared with traditional cellular materials such as foams or honeycomb cores, lattice structures offer a much greater design freedom. Because the cell topology (e.g., re-

entrant, chiral, arrowhead), strut wall thickness, cell size, and orientation can be precisely controlled, mechanical properties such as density, elastic modulus, yield strength, and energy-dissipation capacity can be tuned over a wide range (Lu et al., 2023; Peng et al., 2022). Thus, different lattice topologies manufactured from the same base material can exhibit customized performance for different loading scenarios.

Mechanical metamaterials can be considered as a broader subset of lattice structures and essentially refer to structures that exhibit engineered mechanical properties through their geometry. Unusual behaviors such as a negative Poisson's ratio, negative thermal expansion, and wave propagation with band gaps are among the distinctive features of these metamaterials (Dutta et al., 2021; Peng et al., 2022). In realizing such properties, the decisive role belongs to the cell geometry; the base material can often be a conventional linearly elastic polymer, metal, or composite.

The rise of lattice- and metamaterial-based structures is directly related to advances in additive manufacturing technologies. 3D-printing techniques such as FDM, SLA (stereolithography), and SLS (selective laser sintering) enable the precise and repeatable fabrication of complex lattice geometries that were almost impossible to manufacture using conventional machining or molding methods (Essassi et al., 2020; Tunay, 2024; Usta, 2024; Zeng et al., 2022). In particular, polymer-based FDM processes are widely used in academic research because they allow low-cost prototyping and parametric studies (Tunay, 2024; Usta, 2024).

As a result of these developments, many studies in literature focus on how small-scale topological features (e.g., cell-wall thickness, cell angle, porosity distribution) affect the large-scale mechanical behavior of structures (Chen et al., 2024; Shirzad et al., 2024; Usta, 2024; Zhao et al., 2021). The objective is to optimize mechanical performance through functional grading strategies such as using different unit-cell configurations, decreasing or increasing porosity in specific regions of the core, or changing cell size depending on the loading direction (Chen et al., 2024; Shirzad et al., 2024; Yan et al., 2023).

When lattice structures are used as the core layer of sandwich structures, they provide the designer with full control over the micro-architecture of the core. Thus, for example, wall thickness or density can be increased in regions where increased energy dissipation is desired during a collision; in regions where mass savings are required,

sparser topologies can be preferred (Lu et al., 2023; Wang et al., 2023). In this way, both the lightness and mechanical performance of the sandwich structure can be maximized in accordance with the target application.

1.4 Auxetic Structures and Negative Poisson's Ratio

Auxetic structures represent a special class of mechanical metamaterials that differ from conventional materials by having a negative Poisson's ratio (Lu et al., 2023; Usta, 2024; Yan et al., 2023). While traditional materials tend to contract laterally as they extend longitudinally under tensile loading, auxetic structures exhibit expansion in both the longitudinal and transverse directions; similarly, under compressive loading, contraction occurs in both the longitudinal and transverse directions (Chen et al., 2024; Dutta et al., 2021). This unusual deformation behavior arises entirely from cellular geometry and is not directly related to the chemical structure of the material (Dutta et al., 2021).

The most common auxetic geometries are topologies consisting of re-entrant lattices, chiral structures, and arrowhead- and star-shaped cells (Lu et al., 2023; Peng et al., 2022; Usta, 2024). In re-entrant structures, cell walls are bent inward or positioned at an angle; thus, under tension, opening of cell angles results in expansion both in the loading direction and laterally. In chiral structures, a geometry with rotational symmetry enables the cells to rotate and expand under tension (Peng et al., 2022; Yolcu et al., 2025). The design of re-entrant auxetic core structure given in Figure 1.2.

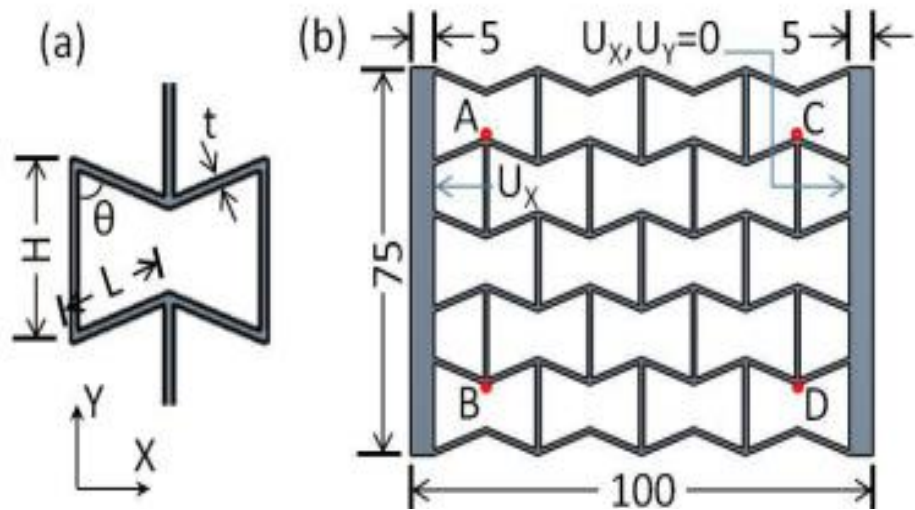


Figure 1.2: Design of the re-entrant auxetic core (a) unit cell and (b) beam structure.

A negative Poisson's ratio provides auxetic structures with several critical mechanical advantages. High indentation resistance can be defined as when a localized load is applied to an auxetic surface, the material tends to flow and densify toward the loading region. This “densification” effect increases the local stiffness of the material and its resistance to penetration, providing superior protection against perforation and sharp impact loads (Dutta et al., 2021; Sengul et al., 2025; Zeng et al., 2022).

Increased energy-dissipation capacity can be expressed as inward folding and successive collapse of auxetic cells under compression result in a wide plastic deformation region in the load–displacement curve and high specific energy-absorption (SEA) values (Essassi et al., 2020; Francisco et al., 2023; Lu et al., 2023; Wang et al., 2023; Xiao et al., 2019).

Another advantage is improved fracture toughness and shear modulus. A negative Poisson's ratio may enable stress concentrations at crack tips to be redistributed differently, making crack growth more difficult and theoretically contributing to a higher effective shear modulus (Peng et al., 2022).

Tunable dynamic and vibration behavior is one of the benefits of a negative Poisson's ratio. Free-vibration and modal analyses of composite panels with auxetic cores have shown that different natural frequencies and mode shapes can be obtained compared with conventional cores (Peng et al., 2022; Yolcu et al., 2025). This offers new design opportunities in areas such as vibration control and acoustic insulation.

Because of these advantages, auxetic structures stand out as promising candidate materials in a wide variety of fields such as the defense industry (ballistic armors, blast-resistant panels), biomedical implants (bone-like lattice scaffolds), sports equipment (helmets and protectors), and vibration-damping applications (Sengul et al., 2025; Shirzad et al., 2024; Yan et al., 2023).

1.5 Use of Auxetic Cores in Sandwich Structures

Sandwich structures and auxetic metamaterials are known to exhibit superior mechanical properties when considered independently. When these two concepts are combined specifically by incorporating auxetic lattice geometries into the core layer of sandwich structures a synergistic design strategy emerges (Lu et al., 2023). In such configurations, the advantages of auxetic cores related to their negative Poisson's ratio,

including enhanced energy absorption, impact resistance, and indentation resistance, are effectively coupled with the high bending stiffness and load-carrying capability provided by the face sheets (Sengul et al., 2025; Usta, 2024). As a result, auxetic cores that may display relatively low absolute stiffness or strength when used alone can function as highly efficient and versatile components within sandwich composites, thereby largely overcoming these inherent limitations (Lu et al., 2023).

One of the most significant benefits of sandwich structures incorporating auxetic cores is their improved resistance to impact and blast loading. The densification behavior of auxetic cores plays a major role in increasing perforation and indentation resistance under localized impact or blast conditions (Xiao et al., 2019; Yan et al., 2023; Zeng et al., 2022). In particular, the sequential snap-through behavior characteristic of re-entrant core geometries leads to an extended deformation range and the formation of multiple peaks in the load–displacement response, which substantially enhances the overall energy absorption capacity (Li et al., 2023; Wang et al., 2023; Zhao et al., 2021). In addition to impact performance, these structures also provide opportunities for tuning dynamic behavior and vibration control. Studies on sandwich panels with negative Poisson’s ratio cores have shown that their natural frequencies and mode shapes differ from those of panels with conventional core designs, and that vibration amplitudes can be reduced within specific frequency ranges (Peng et al., 2022; Yolcu et al., 2025). This indicates that auxetic-core sandwich structures are an attractive solution, especially for lightweight panels requiring noise and vibration control.

However, the performance of auxetic-core sandwich structures varies depending on many parameters such as core geometry (t/l ratio, cell angle, etc.), face-sheet thickness and arrangement (t_f/t_b ratio), and loading conditions (loading rate, impact location, boundary conditions) (Li et al., 2023; Wang et al., 2023; Yan et al., 2023; Zhao et al., 2021). Designing these parameters in interaction with one another is critical for achieving the targeted energy-absorption and weight criteria.

In the context of this thesis, a design discussion is conducted by comparing uniform and functionally graded distributions of cell-wall thickness in re-entrant auxetic-core sandwich beams. In this way, uniform auxetic cores and functionally graded auxetic structures, previously addressed separately in the literature are directly compared under the same material system and experimental conditions.

1.6 Literature Review

In this section, previous studies on the mechanical behavior of auxetic-core sandwich structures are examined in detail. The aim is to summarize the current body of knowledge, reveal the main research trends, and clarify which gap in the literature this thesis study aims to fill.

1.6.1 Parameters for the Performance of Uniform Auxetic Cores

The literature has thoroughly explored the bending behavior of re-entrant auxetic-core sandwich beams under various conditions, including quasi-static three-point bending and impact loads at low and medium velocities (Essassi et al., 2020; Li et al., 2023; Lu et al., 2023; Usta, 2024; Wang et al., 2023; Zhao et al., 2021). These studies systematically analyze how factors such as cell geometry parameters (t/l ratio, cell angle, cell height), face-sheet thickness, and loading conditions (rate, impact location, boundary conditions) influence the load-carrying capacity, energy absorption, and collapse modes of the beams.

The t/l ratio, defined as the ratio of cell-wall thickness to cell-wall length, represents a key geometric parameter that governs the relative density of the core (Zhao et al., 2021). Zhao et al. (2021) demonstrated through a detailed parametric study on re-entrant auxetic-core sandwich beams that increasing the t/l ratio can change the core deformation mode, shifting from overall bending to more localized bending or cell-wall buckling. In the same study, it was reported that as the t/l ratio increases, the first peak force and the absorbed energy in the load–displacement curves increase significantly; however, at very high t/l ratios, strut fracture may be triggered due to stress concentrations.

Li et al. (2023) investigated the three-point bending behavior of sandwich beams with a novel auxetic honeycomb core configuration and, using multi-criteria decision-making methods such as COPRAS, demonstrated that the t/l ratio is the most influential geometric parameter on bending performance. In their study, it was emphasized that the t/l ratio plays a dominant role—depending on the maximum load, specific energy absorption, first peak force, and collapse mode. However, this effect may differ based on the elastic–plastic behavior of the core material, the thickness of the face-sheet, and the boundary conditions (Li et al., 2023; Zhao et al., 2021).

Usta (2024) demonstrated that the influence of the t/l ratio on specific energy absorption (SEA) is strongly dependent on the material system in studies involving hybrid re-entrant cores composed of both flexible and rigid materials. The findings showed that SEA may increase as the t/l ratio decreases, and that deformation behavior can be effectively controlled by incorporating flexible materials in selected regions of the core. These results highlight that the effect of the t/l ratio is closely linked to material selection, core design, and overall geometric configuration.

The mechanical performance of auxetic-core sandwich beams is also significantly influenced by the thickness and arrangement of the face sheets. Zhao et al. (2021) and Wang et al. (2023) reported that increasing face-sheet thickness leads to notable improvements in both energy absorption and maximum load-carrying capacity. Furthermore, Li et al. (2022) showed that configurations with a thicker top face sheet than bottom face sheet ($t_t/t_b > 1$) provide enhanced load-bearing capability and energy absorption under bending, particularly by suppressing localized indentation when the total structural mass is kept constant. In contrast, Yan et al. (2023) suggested that alternative configurations with a thinner top face sheet and a thicker bottom face sheet ($t_t/t_b < 1$) may be more effective under different loading scenarios, such as blast loading, indicating that optimal face-sheet design should be tailored to the specific loading conditions.

Loading conditions play a significant role in governing the energy absorption mechanisms and deformation modes of sandwich beams. In this context, Wang et al. (2023) and Zhao et al. (2021) reported that both the structural strength and specific energy absorption of sandwich beams vary considerably depending on the location of the applied impact load relative to the core cell geometry, namely whether the load is applied at the T-position on the cell wall or at the M-position between adjacent cells. The T-position was reported to offer greater load carrying capacity and energy absorption because it facilitates load transfer through the cell wall. Xiao et al. (2019) and Zeng et al. (2022) observed that higher impact velocities increase the first peak force and absorbed energy due to inertia effects but also cause deformation to become more localized in the loading region, leading to different collapse modes in the core.

In summary, the literature shows that the t/l ratio, face-sheet configuration, and loading conditions play a key role in the mechanical performance of uniform auxetic-core

sandwich beams (Li et al., 2023; Usta, 2024; Wang et al., 2023; Xiao et al., 2019; Zhao et al., 2021; Zeng et al., 2022).

1.6.2 Functionally Graded (FG) Auxetic Structures

In recent years, functionally graded (FG) designs, in which material and/or geometric properties vary gradually within the structure, have attracted increasing attention in the literature as an effective means of improving the performance of sandwich and lattice systems (Chen et al., 2024; Shirzad et al., 2024). Within this design framework, parameters such as cell wall thickness, cell size, or porosity ratio are systematically varied along the height of the structure according to a predefined function. This gradual variation is intended to promote a more favorable stress distribution, regulate deformation mechanisms, and enhance key performance metrics including energy absorption, impact resistance, and structural stiffness (Chen et al., 2024; Yan et al., 2023).

Jin et al. (2016) investigated the dynamic response of graded re-entrant cores produced by stepwise variation of cell wall thickness under blast loading conditions and demonstrated that this strategy can lead to a substantial improvement in energy absorption performance (as cited in Lu et al., 2023; Yan et al., 2023). Their results indicated that negatively graded cores, characterized by thinner cell walls near the top surface and thicker walls toward the bottom, exhibit lower permanent deflection after blast events and a more balanced stress distribution.

In a similar manner, Chen et al. (2024) analyzed various grading strategies, including positive, negative, and symmetric grading, for chiral auxetic-core sandwich panels subjected to blast loading. Their findings revealed that the negatively graded configuration provided the most effective blast resistance, as evidenced by the lowest permanent deflection and the most pronounced negative Poisson's ratio response. Collectively, these results suggest that, under severe dynamic loading conditions such as blast and impact, the use of gradually varying core topology represents a powerful design approach for enhancing the overall mechanical performance of sandwich structures.

With a focus on biomechanical applications, Shirzad et al. (2024) carried out design and optimization studies on functionally graded auxetic lattice structures inspired by natural tissues such as bone and tendon. Their findings showed that graded auxetic

configurations provide significant improvements in both Young's modulus and yield strength when compared with uniform lattice structures. Notably, reducing porosity in the lower part of the graded structure boosts its load-carrying capacity. These findings indicate that graded auxetic structures are a strong candidate not only for impact and blast resistance but also for applications such as biomedical implants where mechanical and biocompatibility criteria are both important.

When functionally graded designs are adapted to auxetic-core sandwich structures, they enable the core density and stiffness to be distributed in accordance with load paths. For example, under bending loads, tensile and compressive regions can be optimized by using different cell-wall thicknesses in the upper and lower regions of the core; for the central shear region, mass savings can be achieved by selecting relatively lower density. In this way, both maximum load-carrying capacity and specific energy absorption values can be improved (Chen et al., 2024; Jin et al., 2016; Yan et al., 2023). Gradient and uniform geometries are shown in Figure 1.3.

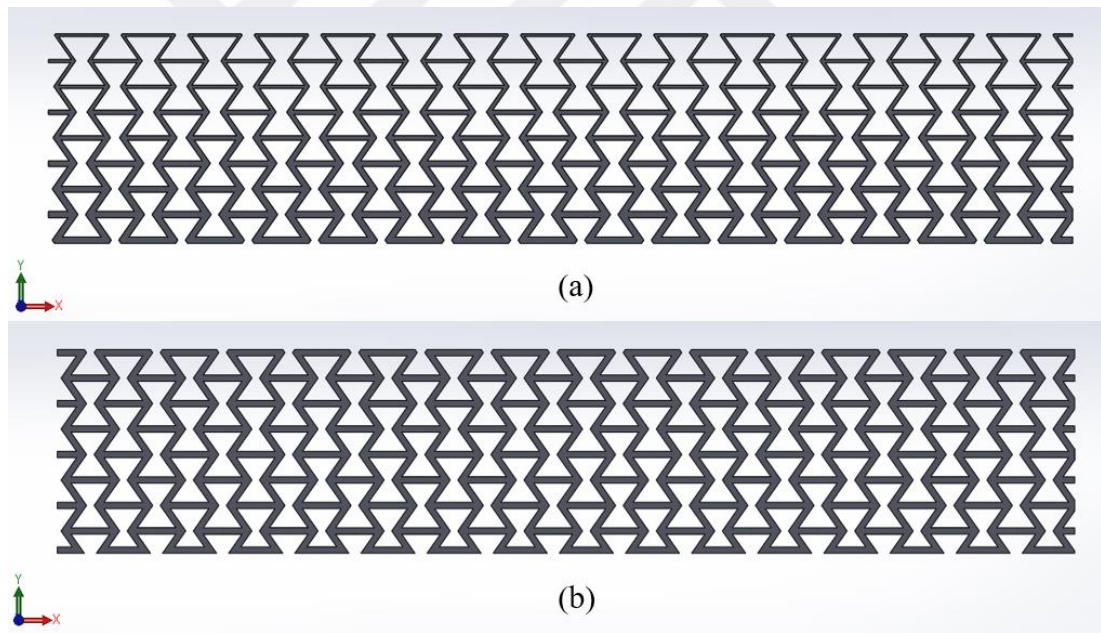


Figure 1.3: (a) Gradient thickness distributed core, (b) Core with uniform thickness.

1.6.3 Research Gap

The literature summarized above clearly shows that parameters such as the t/l ratio, face sheet configuration, and loading conditions play a decisive role in mechanical performance of uniform auxetic-core sandwich beams (Li et al., 2023; Usta, 2024; Wang et al., 2023; Zhao et al., 2021). At the same time, various studies have also

shown that functionally graded auxetic structures have the potential to further improve indicators such as blast resistance, energy absorption, and load carrying capacity by optimizing core properties along the structure (Chen et al., 2024; Jin et al., 2016; Shirzad et al., 2024; Yan et al., 2023).

However, studies that directly and systematically compare these two main design approaches, namely, uniform auxetic cores with different wall thicknesses and functionally graded auxetic cores in which wall thickness is varied stepwise along the structure under the same material system, similar geometric parameters, and similar experimental/numerical conditions are extremely limited in the literature. Most studies either focus only on uniform structures or address only graded designs and do not comprehensively compare these two approaches within the same study.

Therefore, this gap in the literature presents an original research area through the comparison of uniform and functionally graded distributions of cell wall thickness in re-entrant auxetic core sandwich beams. The present thesis study is designed to fill this gap and aims to produce comparative results by investigating the bending behavior of sandwich beams with uniform and graded cores under the same material combination and similar geometric parameters both experimentally and using the finite element method.

1.7 Aim and Scope of the Thesis

In light of the literature summarized above and the identified research gap, the main aim of this thesis study is to investigate in detail the bending behavior of re-entrant auxetic-core sandwich beams by comparing uniform and functionally graded (FG) core configurations with different cell wall thicknesses. The study aims to determine which design strategy is more advantageous for specific performance objectives (e.g., maximum energy absorption, minimum weight at a certain stiffness level, a certain collapse mode). Also, foam-filled re-entrant sandwich beam is produced and tested. Hence, the effects of foam filling operation are observed. The comparison of the specimens with an another scope was possible.

To achieve this general aim, the following specific objectives have been defined. First of all, specimen design and fabrication have a crucial importance. Sandwich beam

specimens with re-entrant auxetic cores using AA1050 aluminum as the face-sheet material and PLA produced by the FDM method as the core material are designed.

Uniform re-entrant auxetic cores with different constant wall thicknesses (e.g., low, medium, high t/l ratios) are manufactured.

Functionally graded (FG) re-entrant auxetic cores in which the cell wall thickness is varied stepwise along the beam height (e.g., positive, negative, or symmetric grading strategies) designed and manufactured.

Then, Experimental analyses have been done. Three-point bending tests on all sandwich beam specimens in accordance with relevant standards to obtain load–displacement curves are performed.

Crashworthiness performance metrics such as maximum load, yield load, global stiffness, elastic limit, collapse mode, total and specific energy absorption from these curves are calculated.

Deformation mechanisms using high resolution imaging techniques (e.g., photo or video recordings) observed and characterized.

Each specimen three times to increase the reliability of the results tested.

Numerical modeling and validation have been done. Finite element models consistent with the experimental specimens and define appropriate material models (elastic–plastic for AA1050; appropriate elastic–plastic model for PLA) are created.

Boundary conditions and loading conditions in accordance with the experimental setup are modeled, and parameters such as contact and mesh structure are calibrated.

The model by comparing the numerical results with the experimental data is validated.

Comparative performance evaluation is one of the necessary studies. Based on the obtained experimental and numerical results, uniform and functionally graded re-entrant-core sandwich beams are compared in terms of load-carrying capacity, energy absorption capacity, collapse mode, stiffness, and mass efficiency.

The effects of various wall thickness distributions on performance are examined parametrically and the best design approaches for particular performance goals are described.

A specimen reinforced with foam material is manufactured and tested. Then its bending behavior with that of specimens without a filling material is compared.

At conclusion, practical design principles and recommendations for the design of re-entrant auxetic core sandwich beams in line with the findings obtained are presented. Research recommendations for future studies regarding material, geometry, manufacturing method, and loading conditions are developed.

1.8 Contribution to Literature

This study aims to provide significant and original contributions to existing literature from multiple perspectives.

First, the study offers a directly comparative perspective by filling an important gap in literature. Although many studies exist separately on uniform auxetic cores and functionally graded auxetic structures (Chen et al., 2024; Jin et al., 2016; Li et al., 2023; Shirzad et al., 2024; Zhao et al., 2021), studies that compare these two design philosophies under the same material system and similar experimental conditions particularly through the cell-wall thickness parameter both experimentally and numerically are quite limited. This thesis study fills this gap by directly comparing these two approaches in the context of re-entrant auxetic core sandwich beams.

The second original contribution is the specific material combination used. The combined use of Al1050 aluminum as the face sheets and PLA produced by the FDM method as the core material is a material pair that has been less studied in literature. This material combination has the potential to provide valuable data for the development of sustainable composite structures owing to features such as light weight, recyclability, and ease of manufacturing (Essassi et al., 2020; Tunay, 2024; Zeng et al., 2022). In addition, foam-core sandwich beams are also considered in this study, and the behavioral differences associated with this type of filled cellular structure are discussed in detail.

Another distinguishing aspect of the present work is the combined use of experimental testing and numerical modeling, which differentiates it from studies based solely on numerical simulations or limited experimental observations. Finite element models validated against experimental results enable the prediction of the effects of various geometric and material parameters under conditions that are difficult or costly to

reproduce experimentally (Dutta et al., 2021; Usta, 2024). As a result, the outcomes of this study provide a higher level of reliability and practical relevance for engineering applications.

Finally, the findings of this thesis offer a practical design framework for engineers working on auxetic-core sandwich structures. By identifying suitable geometric and material parameters for specific performance targets—such as enhanced load-carrying capacity, improved impact resistance, and weight reduction, the study delivers actionable design insights. These contributions support a deeper understanding of the design and optimization of auxetic-core sandwich structures and are expected to be valuable for both academic research and engineering practice.



2. MATERIALS AND METHOD

2.1 Materials and Material Characterization

In this study, aluminum alloy AA1050 was used as the face-sheet material of the sandwich beam, while polylactic acid (PLA) was selected for the core. AA1050 was chosen mainly because of its excellent formability, low density, and relatively high elastic modulus. In addition, it offers favorable electrical and thermal conductivity, along with high corrosion resistance. Its cost-effectiveness and ease of machining contribute to achieving sufficient flexural stiffness from a mechanical standpoint and make the material well suited for prototype manufacturing.

Owing to its low density of approximately 1.25 g/cm^3 , compatibility with additive manufacturing techniques, and ability to form complex auxetic cell geometries, PLA represents a suitable choice for the core material. With an elastic modulus of about 2.5 GPa, it is capable of sustaining shear loads at an adequate level for the intended application. Moreover, its biodegradable and environmentally friendly nature is one of the main reasons PLA is widely preferred in academic and laboratory-based studies. Together, these two materials enable the formation of a sandwich structure that achieves a balance between manufacturability and mechanical performance. Accordingly, this material selection provides a reliable basis for both numerical and experimental investigations of the flexural behavior of the structure.

PLA (polylactic acid) re-entrant core structures and AA1050 aluminum face sheets were used to create the auxetic sandwich beams under investigation in this study. Using a three-dimensional printer, the re-entrant cores were created as specimens with various wall thickness values and thickness configurations, set up for mechanical testing.

2.1.1 AA1050 Aluminum Face Sheets

Upper and lower face sheets of the beams were made of aluminum alloy AA1050, which is known for its excellent ductility and great formability. In order to isolate the

impact of the core geometry while comparing various core configurations, the face-sheet thickness was maintained at 0.5 mm for all specimens.

The elastic mechanical properties of AA1050, namely the elastic modulus (E), shear modulus (G), Poisson's ratio (ν), and density, were obtained from tensile tests conducted on material specimens within the scope of this study. The material properties are summarized as; elastic modulus is $E = 19,120$ MPa. Shear modulus is $G = 7,187.95$ MPa. Poisson's ratio is $\nu = 0.30$ and, density is $\rho = 2.71$ g/cm³

These values were directly implemented in the material definition for the finite element analyses and were also used as background information to support the interpretation of the global structural response of the sandwich beams in the experimental evaluations.

2.1.2 PLA Core Material

Polylactic acid (PLA)-based filament was used for manufacturing the re-entrant core structures. PLA is a thermoplastic widely employed in FDM (Fused Deposition Modelling)-based three-dimensional printers and typically exhibits relatively rigid and brittle behaviour. The elastic properties of the PLA filament used in this study were obtained from tensile tests performed within the scope of this work, whereas the density range was taken from the technical datasheet. The filament used belongs to the Filamix brand.

The properties of the PLA material are as follows: elastic modulus is $E = 2500$ MPa. Shear modulus is $G = 468$ MPa. Poisson's ratio is $\nu = 0.30$. Ultimate tensile strength is $\sigma_u = 39.1$ MPa and density is $\rho = 1.27$ g/cm³.

These parameters were considered as the primary material inputs in both the experimental and numerical analyses of the re-entrant cores. Since PLA is sensitive to material orientation, the tensile tests were planned to represent the printing direction used during specimen fabrication, with the aim of ensuring that the elastic properties employed in the finite element model were consistent with the actual manufacturing orientation. Particular attention was paid to aligning the filament deposition with the tensile loading direction. In this manner, the material properties were extracted in the strongest direction.

2.1.3 Adhesive System (Epoxy Resin)

A two-component epoxy-based resin system was used to bond the face sheets to the PLA core structure. The hardener and resin components were mixed at a mass ratio of 35/65. The epoxy system was selected to obtain a continuous bond between the face sheet and the core, and to approximate the sandwich beam behavior as closely as possible to ideal conditions.

The epoxy mixture was prepared in accordance with the manufacturer's instructions, and the specimens were left to cure at room temperature without applying any external pressing. In the finite element model, this bond was represented by the assumption of a perfect bond. Accordingly, no relative sliding, separation, or damage was assumed to occur at the interface between the two parts, and the interfacial contact definitions in the numerical models were specified in line with this assumption.

2.1.4 Polyurethane Foam as an Additional Implementation

All six primary scenarios forming the main body of this study were investigated without filling the core voids (i.e., considering only the re-entrant cellular structure). In addition, polyurethane (PU) foam was used to fill the core cavities only for the re-entrant cell geometry with a uniform wall thickness of 0.75 mm, in order to observe the filling effect within a limited scope for this specific case.

The foam is a two-component system consisting of isocyanate and polyol constituents. The mixing ratio was determined on a mass basis as 128 g isocyanate / 100 g polyol, in accordance with the manufacturer's recommendations. The preparation of the mixture was carried out using a controlled procedure to ensure safety and to prevent chemical contamination, and the foam production was considered as an additional implementation rather than the focus of the study. The foam-filled specimens that are manufactured for the study are given in Figure 2.1.

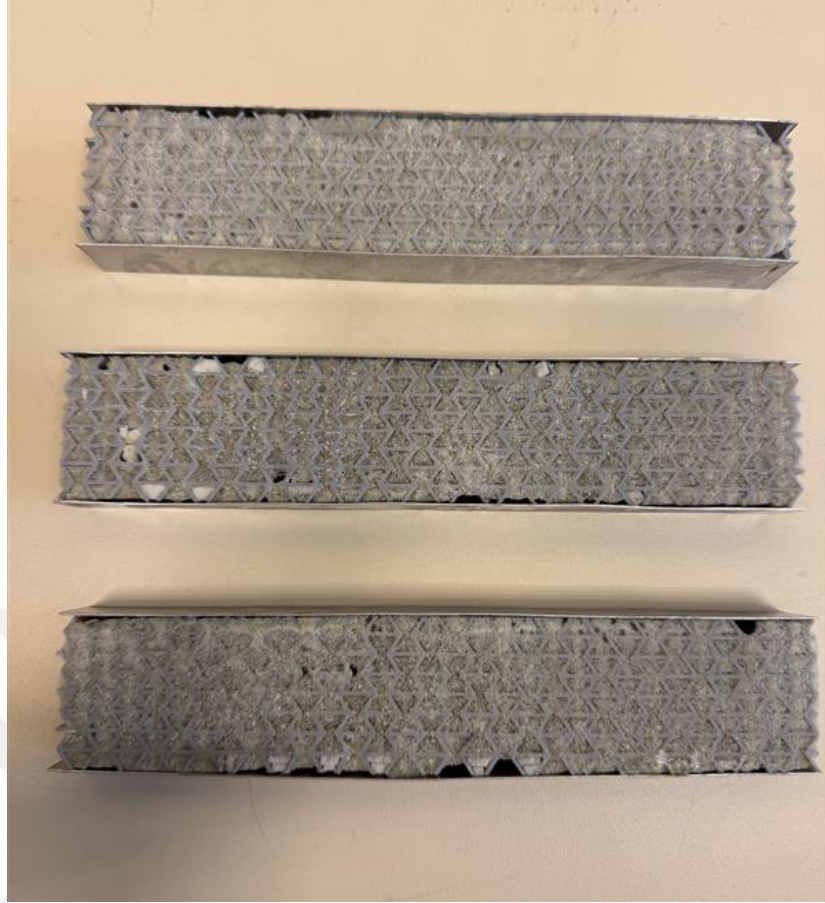


Figure 2.1: The specimens that are filled with PU foam.

2.2 Specimen Geometry and Definition of Scenarios

In this study, the flexural behavior of sandwich beams with a re-entrant core geometry was investigated. The global geometry of the beam was kept constants for all specimens, and only the distribution of the wall thicknesses of the re-entrant cells was varied among the specimens. In this way, the effects of cell-wall thickness and its position-dependent distribution on flexural stiffness, load-carrying capacity, and deformation behavior could be systematically evaluated.

2.2.1 Overall Geometry of the Beam

Each sandwich beam specimen has the following dimensions. beam length of the specimens is 200 mm. Beam width is 20 mm. Total core thickness of the beams are 40 mm, and face-sheet thickness are 0.5 mm while top and bottom sheets are constant.

The re-entrant core structure consists of an arrangement of cells organized as 4 cells through the thickness direction and 20 cells along the beam length in lateral direction. Accordingly, each specimen includes a re-entrant core with a 20×4 cell array. The characteristic angles and lengths of the cell geometry were kept identical in all scenarios, and only the cell-wall thickness values were modified. Thus, the geometric variability was reduced to a single parameter: the wall thickness and its distribution.

2.2.2 Re-entrant Cell Wall Thickness Scenarios

The six different core specimens investigated in the present study are defined as follows:

Specimen 1 has wall thickness increasing from top to bottom. The cell-wall thickness through the core thickness was defined to increase from top to bottom by 0.5 mm, 0.75 mm, 1.0 mm, and 1.25 mm, respectively. The corresponding geometry is shown in Figure 2.2.

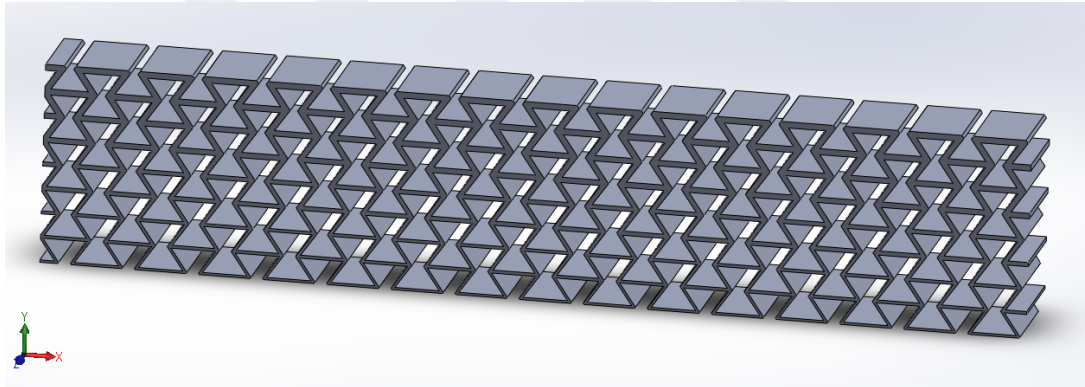


Figure 2.2: Specimen 1 core geometry.

Specimen 2 has wall thickness decreasing from top to bottom. In this configuration, the cell-wall thickness through the core thickness was modelled with a decreasing distribution from top to bottom as 1.25 mm, 1.0 mm, 0.75 mm, and 0.5 mm, respectively. The corresponding geometry is presented in Figure 2.4.

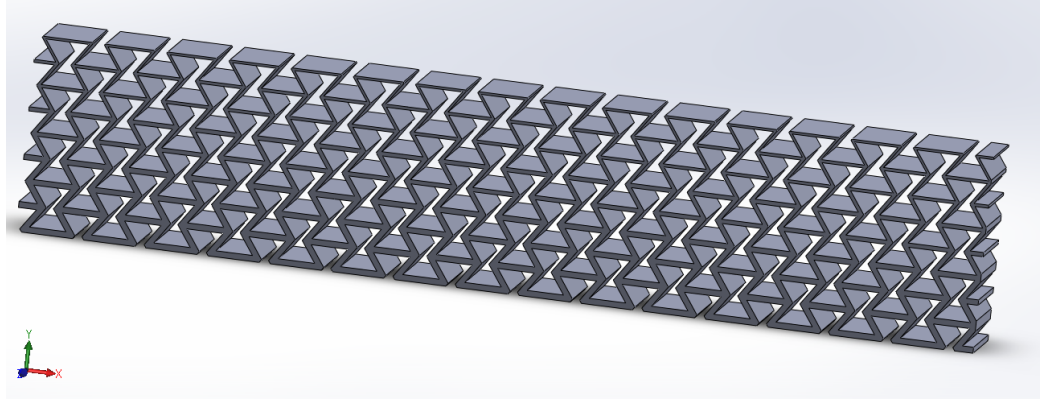


Figure 2.4: Specimen 2 core geometry.

Specimen 3, uniform wall thickness of 0.5 mm. The cell-wall thickness was kept uniform at 0.5 mm throughout the entire core. The corresponding geometry is shown in Figure 2.3.

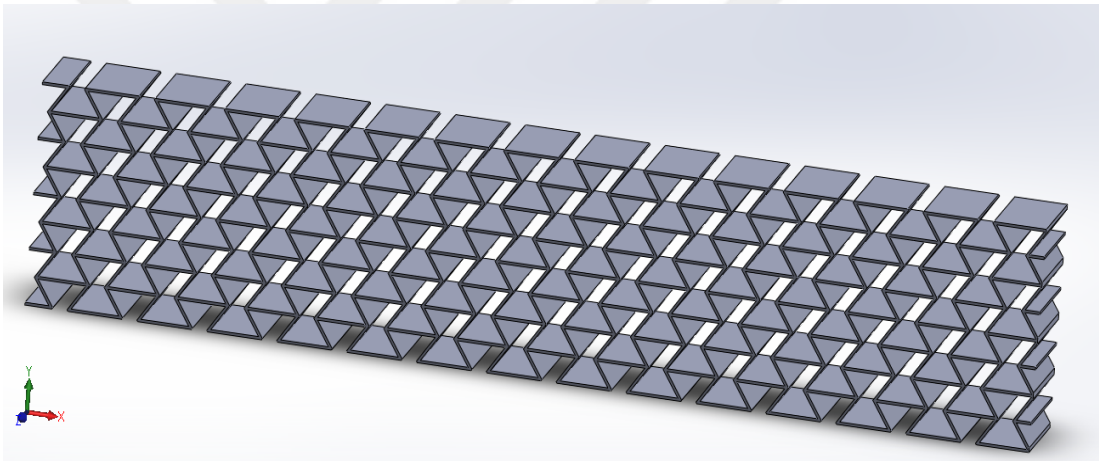


Figure 2.3: Specimen 3 core geometry.

Specimen 4 has uniform wall thickness of 0.75 mm. The wall thickness was defined as uniform at 0.75 mm throughout the entire core.

Specimen 5 has uniform wall thickness of 1.0 mm. The wall thickness for all cell walls was set to 1.0 mm.

Specimen 6 has uniform wall thickness of 1.25 mm. In the scenario with the highest wall thickness along the core, the wall thickness was kept constant at 1.25 mm.

For each scenario, one sandwich beam specimen was fabricated and subjected to an experimental three-point bending test. In this manner, six different re-entrant configurations were made comparable under identical loading conditions. In addition,

an extra specimen was produced only for the geometry of Specimen 4, in which the core cavities were filled with polyurethane foam, and the response of this specimen was evaluated as a reference, particularly in terms of load-carrying capacity and deformation characteristics.

2.3 Specimen Manufacturing

Specimen manufacturing consisted of fabrication of the PLA cores by three-dimensional printing, preparation of the AA1050 face sheets and bonding them to the core, and application of foam filling for only one specimen.

2.3.1 Fabrication of PLA Cores by 3D Printing

The re-entrant core geometries were modelled in a CAD environment, and separate STL files were created for each scenario. These models were transferred to a FDM-type 3D printer, namely the Bambu Lab X1-Carbon. Prior to printing, the printing parameters were defined in the slicing software to be identical for all specimens, regardless of scenario differences.

The main printing parameters were as follows, nozzle diameter is 0.4 mm, infill density is 100%, build plate temperature is 110 °C, and nozzle temperature is 220 °C.

The infill density was selected as 100% in order to manufacture the PLA walls with a fully solid cross-section, thereby ensuring that the mechanical behavior of the core walls would not be affected by internal voids. In order to maintain consistency between the printing direction and the elastic properties used in the numerical and experimental analyses, the printing orientation was selected by considering the loading directions applied to the core structure. The manufactured specimens are given in Figure 2.5.

After printing, the core specimens were carefully removed away from the build plate, any potential support structures were cleaned, and the specimens' surface quality and geometric integrity were examined visually. The specimens were approved for use in the following phases as long as no geometric deviations were found.

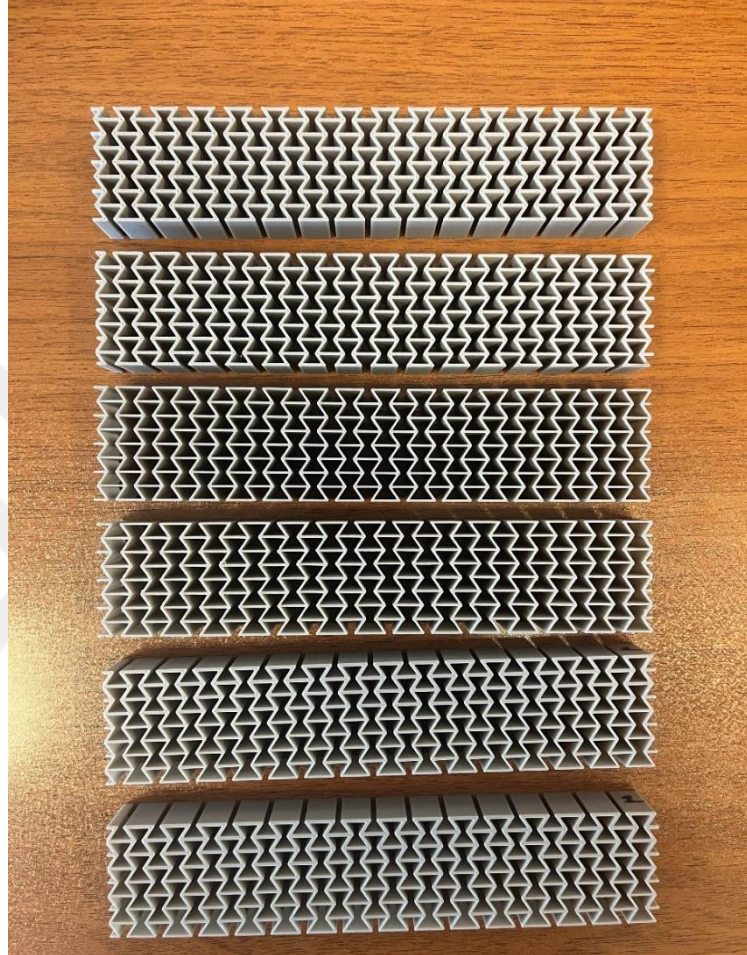


Figure 2.5: Manufactured specimens.

2.3.2 Preparation of Face Sheets and Bonding Procedure

Two plates at the top and bottom were prepared for each specimen after AA1050 aluminum sheets were cut to the required dimensions of 20 mm × 200 mm. Sandpaper or the proper hand tools were used to remove any particles and sharp edges that potentially formed on the surfaces after cutting. To improve adhesion performance, the plates' surfaces that would come into contact with the core were slightly roughened.

The manufacturer's instructions were followed in the preparation of the epoxy resin system used in the bonding process. In an appropriate mixing container, the hardener and resin components were combined at a mass ratio of 35/65 and manually stirred until a homogenous mixture was achieved. The prepared epoxy was applied as a thin and continuous layer to the upper and lower surfaces of the core, after which the AA1050 plates were carefully placed. At this stage, particular attention was paid to ensuring that the face sheets were positioned parallel to the core, that edge alignments were maintained, and that no gaps formed along the specimen length. The specimens were allowed to be cured at room temperature under their own weight. The prepared face sheets and representations of bonding processes are shown in Figure 2.6.



Figure 2.6: Prepared face sheets and bonding process.

2.3.3 Additional Foam-Filling Application

In addition to the primary scope of the study, polyurethane foam filling was applied to a single specimen, specifically the core with a uniform wall thickness of 0.75 mm, in order to fill the internal cavities of the core. This supplementary configuration was introduced to qualitatively investigate the influence of internal foam filling on the overall flexural performance of the sandwich beam.

The foam production process involved several preparation steps. Initially, the metal mold was cleaned using a paper towel soaked in acetone to remove any residual chemicals. Subsequently, a mold release agent was applied with linear strokes to ensure uniform coverage over the entire mold surface. Throughout the procedure, appropriate personal protective equipment, including gloves and safety glasses, was worn to maintain safe handling conditions. Dilution process is shown in Figure 2.7.



Figure 2.7: Products left to be diluted with acetone.

In preparation of constituents, to minimize the risk of isolation and contamination, the isocyanate, polyol, and acetone were measured separately into individual containers. After each use, the container lids were sealed with paraffin tape to prevent unintended mixing and potential contamination.

In mixture preparation, the components were sequentially added to the mixing container, beginning with 128 g of isocyanate followed by 100 g of polyol. All masses were measured using a precision balance, and minor deviations were allowed within the manufacturer's specified tolerance limits.

The mixture was stirred using a mechanical mixer operating at 2100 rpm for 15 s. During mixing, the operator holding the container applied gentle circular motions to assist in achieving a homogeneous mixture.



Figure 2.8: Produced foam element.

In casting and curing process, the prepared mixture was poured into a metal container representing the internal volume of the specimen core (or into the relevant cavity volume), and the container was gently moved to allow the mixture to spread over the surface. The mixture was left to rest for approximately 15 min to allow foaming and volumetric expansion to be completed. The produced foam is shown in Figure 2.8.



Figure 2.9: Cell voids were filled by pouring foam onto the specimen.

This additional application was performed only for the geometry of this specimen, and a detailed mechanical characterization of the foam material is not within the main scope of the present study. Foam filling of the specimen and curing are given in Figure 2.9 and Figure 2.10, respectively.



Figure 2.10: Curing process of the PU foam.

2.4 Three-Point Bending Tests

2.4.1 Test Standard and Testing Machine

Three-point bending tests were conducted to examine the flexural behavior of the sandwich beam specimens. The experiments were planned based on ASTM C393-00, which is widely used for determining the flexural strength and core shear rigidity of sandwich structures.

All tests were performed using an Instron 5569 universal testing machine. The maximum loading capacity of the machine is 50 kN, and the system is equipped with a load cell of appropriate capacity for force measurements. Load and displacement data were recorded through Instron's control and data acquisition software. All tests were carried out at room temperature without any dedicated temperature-control setup.

2.4.2 Test Setup and Parameters

The test setup followed the conventional three-point bending configuration consisting of two lower supports and one upper loading nose. The distance between the centers of the lower supports was set to 160 mm. Thus, the 200 mm-long specimen was placed on the supports leaving a margin at both ends. The test setup is given in Figure 2.11.

The load was applied at the exact mid-span of the specimen using a cylindrical loading nose with a diameter of 5 mm. Selecting an appropriate cylinder diameter aimed to prevent excessive stress concentration along the line of contact between the loading nose and the specimen.

Loading was applied under displacement control. The crosshead of the testing machine was set to move downward at a speed of approximately 14.87 mm/min (≈ 15 mm/min) during the test. This loading rate enables the sandwich beams to be loaded at an almost quasi-static rate and allows viscoelastic/rate-dependent effects of the material to remain at a minimum level.

During the test, the following quantities were recorded as a function of time via the machine software: applied load (F) and crosshead displacement (δ).

The resulting load–displacement data were subsequently used for curve processing, stiffness determination, and identification of the maximum load carrying capacity.

Three sandwich beam specimens were tested for each configuration. In addition, the foam-filled specimen produced for the selected uniform thickness configuration was also subjected to three-point bending under the same conditions.

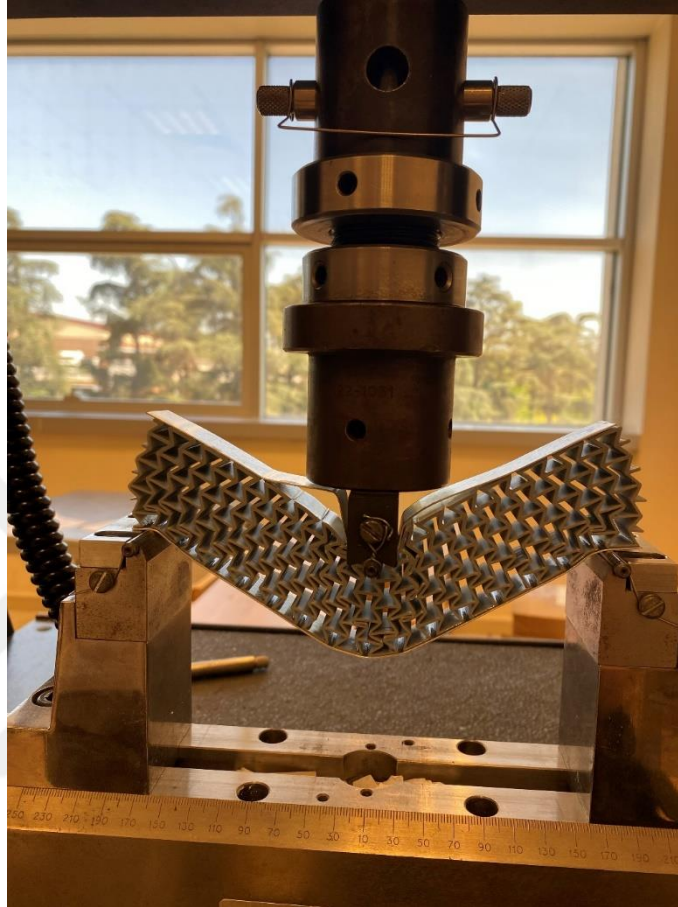


Figure 2.11: 3 point bending test sample.

2.5 Finite Element Analysis

To numerically support the experimental results and to enable detailed examination of stress–strain distributions within the re-entrant core geometry, three-point bending analyses were performed using the Abaqus finite element software.

2.5.1 Geometric Modelling and Mesh Structure

The sandwich beam geometries are designed and imported into Abaqus from CAD models, and a separate model file was prepared for each scenario. The model included

top and bottom AA1050 face sheets, PLA re-entrant core structure and boundary conditions represent the support elements and loading region.

All specimen components were modelled as three-dimensional bodies, and the material and geometric definitions were made consistent with the actual specimen dimensions. Face sheets and rigid test elements were modelled with two-dimensional shell elements

A three-dimensional tetrahedral (tet) solid element mesh was employed. Element edge lengths were selected within the range of approximately 0.5–1.25 mm, considering the geometric complexity in different regions of the sandwich structure. Smaller element sizes were preferred in the thin regions of the re-entrant core walls, whereas relatively larger elements were used in geometrically simpler regions. This approach aimed to both control computational cost and capture stress distributions with sufficient accuracy. The finite element model is given in Figure 2.12 as an example.

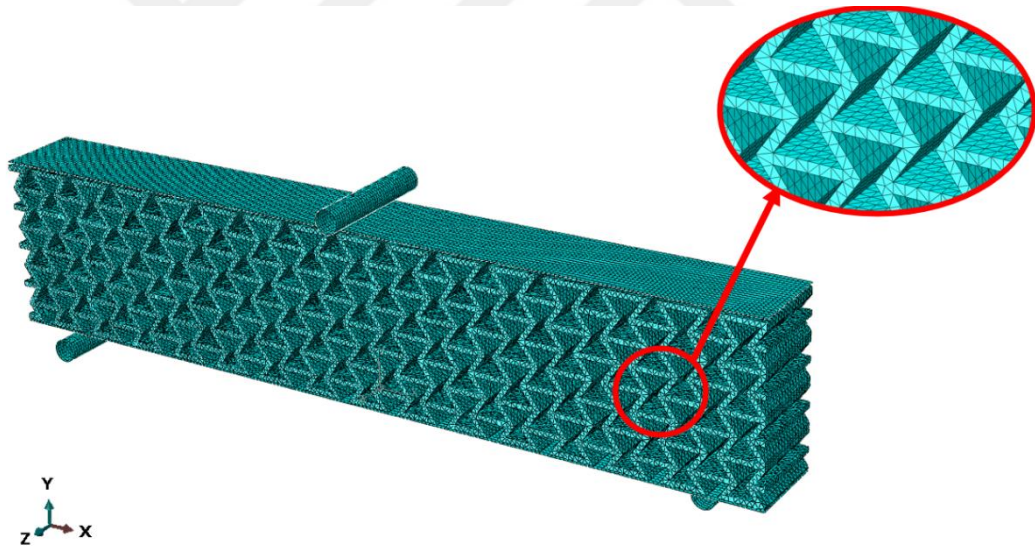


Figure 2.12: FE model of the constructed three-point bending test of the beam.

2.5.2 Material Models

In the finite element analyses, a linear elastic material model was used for both AA1050 and PLA. Material definitions were based on the elastic modulus, shear modulus, and Poisson's ratio values given in Sections 2.1.1 and 2.1.2. Since the foam-filled configuration is not the primary focus of this study, it was treated using a

simplified material approach intended to represent the effect of filling on the global elastic response; the detailed nonlinear crushing behavior of the foam was excluded from the scope of the present work.

2.5.3 Contact Definitions and Connection Conditions

Since the bond between the face sheets and the PLA core was achieved using epoxy during specimen fabrication, perfect adhesion was assumed at this interface in the finite element model, and a tie constraint was applied between the corresponding surface pairs. Accordingly, no relative sliding or separation was allowed between the face sheets and the core.

Surface-to-surface contact definitions were used where necessary in the support and loading regions. Normal contact behavior was defined as hard contact, enabling non-penetration while allowing separation as required. This ensured that the contact between the specimen and the boundary condition components at the support and loading regions behaved realistically.

2.5.4 Boundary Conditions and Loading

To represent the three-point bending conditions, boundary conditions constraining the vertical displacement of the specimen were defined at the regions located beneath the lower supports. A modelling approach approximating support behavior was achieved by preserving the necessary degrees of freedom in the horizontal direction.

Loading was applied through a time dependent displacement imposed at a reference point defined at the mid-span of the specimen. The analysis was conducted using the explicit solution method. By applying a prescribed displacement at the mid-span over the specified analysis duration, time–force and time–displacement outputs were obtained. In this manner, the displacement-controlled loading used in the experiments was also represented in the numerical model.

2.5.5 Analysis Outputs

The Abaqus analyses provided the following outputs: reaction force, displacement, stress and strain distributions throughout the sandwich beam, internal energy and kinetic energy.

Load–displacement curves were derived using the reaction force and mid-span displacement, and comparisons with the experimental curves were performed within the same reference framework. An output example as a plot is given in Figure 2.13.

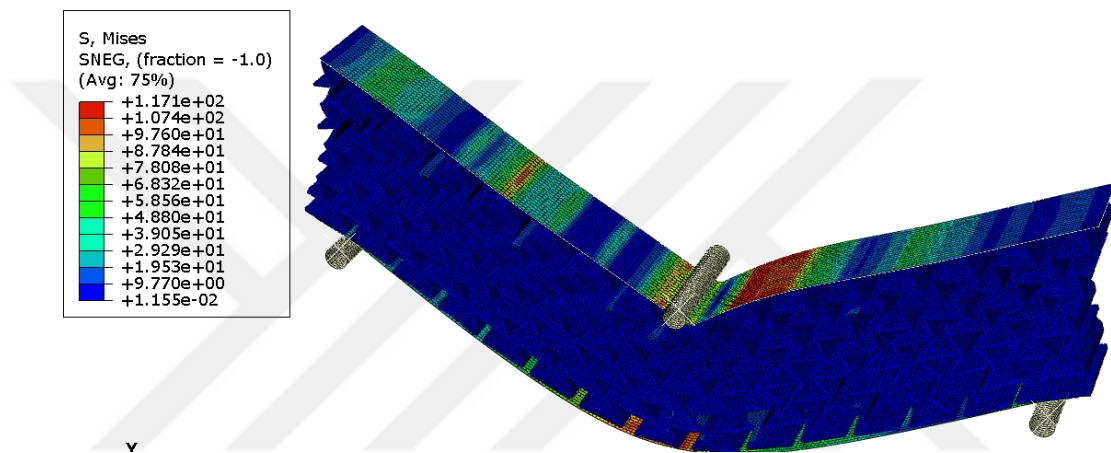


Figure 2.13: Instance for plotting of solved analyses by Abaqus software.

2.6 Evaluation of Experimental and Numerical Results

The load–displacement curves obtained from the experimental three-point bending tests were compared with the numerical load–displacement curves obtained from the finite element analyses. The comparison is primarily considered as maximum load-carrying capacity, slope in the elastic region (global stiffness), mid-span displacements, qualitative observations of failure behavior.

Moreover, the six re-entrant configurations were compared with each other, and the effects of wall thickness and thickness distribution on the flexural response were discussed. The foam-filled additional specimen produced for the uniform 0.75 mm wall thickness configuration (Specimen 4) was evaluated outside the main comparison

scope for reference purposes and interpreted only based on a limited set of key parameters (maximum load, displacement, and stiffness).



3. DISCUSSIONS

In this section, the experimental three-point bending results and the numerical results obtained for the six auxetic core specimens were evaluated together, and the performance differences among specimens were discussed quantitatively in terms of flexural stiffness, ASTM-based nominal flexural stress, mass-specific maximum nominal stress ($\sigma_{\max}/m$), and mass-specific energy absorption capacity (E/m). In addition, the deformation mechanisms were examined qualitatively and related to the obtained quantitative results. In the final part, the foam-filled specimens, produced at the same thickness and tested in three repeats, were reported and comparatively interpreted with respect to Specimens 1–6.

The experimental stress quantity was taken as Flexure stress (MPa) in the test output. This quantity corresponds to the nominal flexural stress calculated based on the sigma expression defined in the ASTM standard used in the test and is denoted by (σ) in this section. Therefore, the expressions of maximum stress were evaluated based on the nominal stress values defined within the standard. The energy absorption capacity was obtained by numerical integration of the area under the load–displacement curve; to eliminate the effect of mass, $\sigma_{\max}$ and E were normalized by mass.

3.1 Quantitative Results and Comparison

For Specimens 1–6, experimental and numerical quantitative data is presented in separate tables in Table 3.1 and Table 3.2.

The stiffness for bending, maximum load capacity, maximum stress that be obtained, energy absorption and its representations for unit mass for experimental results are given in Table 3.1.

Table 3.1: Experimental results for all specimens.

Specimen	Thickness	k (N/mm)	F _{max} (N)	σ _{max} (MPa)	E (J)	σ _{max} /m (MPa/kg)	E/m (J/kg)
1	Increases from top to bottom gradually (0.5-1.25 mm)	57.4	636.6	4.2	28.7	64.4	437.0
2	Increases from bottom to top gradually (1.25-0.5 mm)	47.0	655.4	4.1	20.4	62.5	310.5
3	Uniform 0.5 mm	27.4	359.5	2.4	12.0	58.3	298.0
4	Uniform 0.75 mm	30.9	423.0	2.7	15.5	49.9	288.7
5	Uniform 1 mm	62.4	643.1	4.3	10.4	62.5	149.6
6	Uniform 1.25 mm	123.5	1023.2	6.9	23.2	83.6	281.5

The stiffness and maximum load capacity, KE/IE ratio and work for FE results are given in Table 3.2. The evaluations of the results are provided in discussion and results.

Table 3.2: Numerical results for all specimens.

Specimen	Thickness	k (N/mm)	F _{max} (N)	KE/IE	Work (J/kg)
1	Increases from top to bottom gradually (0.5-1.25 mm)	66.8	659.0	0.05	199.8
2	Increases from bottom to top gradually (1.25-0.5 mm)	66.4	340.9	0.08	108.7
3	Uniform 0.5 mm	20.2	121.0	0.08	66.8
4	Uniform 0.75 mm	26.0	155.8	0.06	78.2
5	Uniform 1 mm	35.9	215.0	0.1	103.5
6	Uniform 1.25 mm	73.8	1070.4	0.04	159.0

3.2 Flexural Stiffness and Load-Carrying Capability

The flexural stiffness k was determined as the slope of the initial linear region of the load–displacement curve.

$$k = \frac{\Delta F}{\Delta \delta} \quad (3.1)$$

The calculated k is bending stiffness (N/mm), ΔF is increase in elastic applied load in the region (N) and $\Delta \delta$ is corresponding midpoint displacement increase (mm). In the calculations, the region where variable elastic performance is valid is selected, and the stiffness value is determined by recording the prevalence in this region.

Under three-point bending, assuming linear elasticity and small deformation, the midpoint displacement is expressed according to the classical Euler–Bernoulli beam theory as follows:

$$\delta = \frac{FL^3}{48EI} \quad (3.2)$$

Within the relationship, theoretical flexural stiffness can be written as follows:

$$k = \frac{F}{\delta} = \frac{48EI}{L^3} \quad (3.3)$$

E is elastic modulus of the material used, I is the equivalent second area moment of the beam, L is the span between the supports. The expression is given as a reference to show the relationship between experimentally obtained global stiffness and structural parameters.

According to the experimental results, a clear separation in stiffness was observed among specimens at Table 3.1 and Figure 3.1. The highest initial stiffness was obtained for Specimen 6 ($k \approx 123.47$ N/mm), followed by Specimen 5 ($k \approx 62.37$ N/mm) and Specimen 1 ($k \approx 57.36$ N/mm). The lowest stiffness was measured for Specimen 3 ($k \approx 27.43$ N/mm). These results indicate that the core configuration significantly changes the global flexural stiffness in the small displacement regime.

Although stiffness is a parameter representing only the elastic region, it provides a strong indicator of the load transfer mechanism at the early stage under bending. In specimens with higher initial stiffness, a higher load increment is observed for small

deformations; this suggests that the load transfer path operates more effectively. In the curves to be presented in Figure 3.1, the steeper initial slope of Specimen 6 will clearly reflect this tendency. However, how the increase in stiffness is reflected in the energy absorption behavior as deformation progresses was evaluated together with the energy metrics in the following subsections.

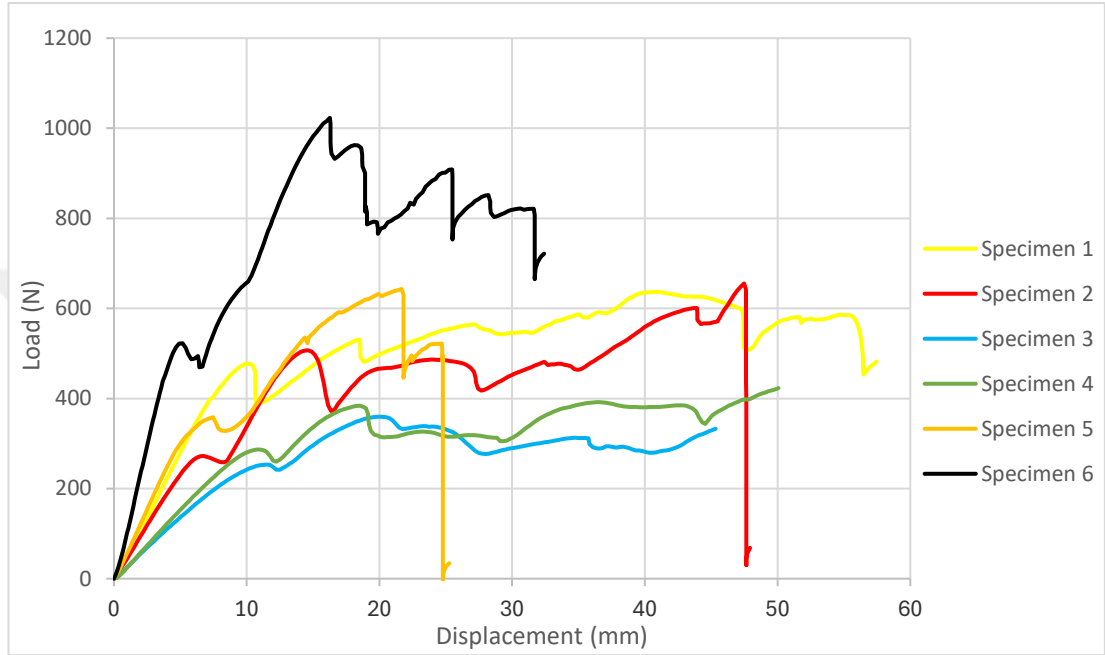


Figure 3.1: Experimental load–displacement curves.

When the reaction force – displacement curves obtained from the numerical results are examined, it is observed that the stiffness trend among specimens can be tracked at the global response level at Table 3.2. This indicates that the stiffness differences do not arise solely from the experimental measurement, and that the changes in configuration are decisive in the global response.

According to the numerical results given in Table 3.2, the finite element model also captured a clear difference in stiffness among the specimens. Similar to the experimental trend, specimen 6 exhibited the highest bending stiffness in the numerical analysis $k = 73.8 \text{ N/mm}$, while specimen 3 showed the lowest stiffness $k = 20.2 \text{ N/mm}$. Specimens 1 and 2 yielded relatively high stiffness values in the FEM results $k = 66.8$ and 66.4 N/mm , respectively, where specimens 4 and 5 remained at intermediate levels $k = 26.0$ and 35.9 N/mm . In this respect, the numerical model was able to reproduce the general tendency that increasing cell-wall thickness increases the global stiffness,

and that the thinnest uniform configuration (Specimen 3) provides the most compliant response.

When the numerical and experimental stiffness values are compared, the overall ordering is partially preserved, especially for the low- and high-stiffness boundaries (Specimens 3 and 6). However, some differences are also evident. In particular, Specimen 2 was predicted numerically with a stiffness level close to Specimen 1, while experimentally Specimen 2 showed a lower stiffness than Specimen 1. This indicates that the FEM model captures the effect of thickness increase on stiffness, but the influence of gradient orientation (top-to-bottom vs. bottom-to-top) is not represented with the same sensitivity observed in the experiments.

A similar comparison can be made for the maximum load, $F_{\max}$. In the numerical results, Specimen 6 reached the highest load-carrying capacity, $F_{\max} = 1070.4$ N, which is in good agreement with the experimental observation that Specimen 6 has the strongest peak load response. Specimen 1 also showed close agreement between numerical and experimental peak loads, indicating that the load transfer and peak response of this graded configuration were represented reasonably well in the model.

On the other hand, for Specimens 2–5, the numerical $F_{\max}$ values were considerably lower than the experimental values. This difference is most pronounced for Specimen 2, where the FEM peak load remained much lower despite its relatively high numerical stiffness. This behavior suggests that, although the initial elastic response is represented at a comparable level, the numerical model may predict earlier local instability, damage initiation, or contact-related loss of load transfer, which limits the peak load development in comparison with the experiments.

3.3 Flexural Stress and Stress–Strain Behavior

In the experimental evaluation, the nominal flexural stress is considered using the flexural stress quantity computed with the sigma expression defined in the test standard. This approach provides a consistent framework for comparing different specimens under the same standard.

$$\sigma_f = \frac{3FL}{2bh^2} \quad (3.4)$$

σ_f is the nominal flexural stress, b is the specimen width and h is the total thickness of the specimen that is tested.

The maximum nominal stress values $\sigma_{\max}$ varied significantly among specimens at Table 3.1. The highest $\sigma_{\max}$ was obtained for Specimen 6 (≈ 6.898 MPa), and the lowest value was obtained for Specimen 3 (≈ 2.356 MPa). This distribution is consistent with the maximum load values and indicates that specimens with higher load-carrying capability also provide an advantage in nominal stress capacity.

However, reporting only $\sigma_{\max}$ is not sufficient to fully explain stress behavior. Therefore, the stress–strain curves were presented separately for each specimen, and the pre-/post-peak behavior was incorporated into the discussion. In particular, the post-peak behavior (the sharpness of load/stress drop or more stable stress evolution) is directly related to the energy absorption capacity.

Strain responses of all specimens are provided by the equation in the test standard.

$$\epsilon_f = \frac{3FL}{2bh^2} \quad (3.5)$$

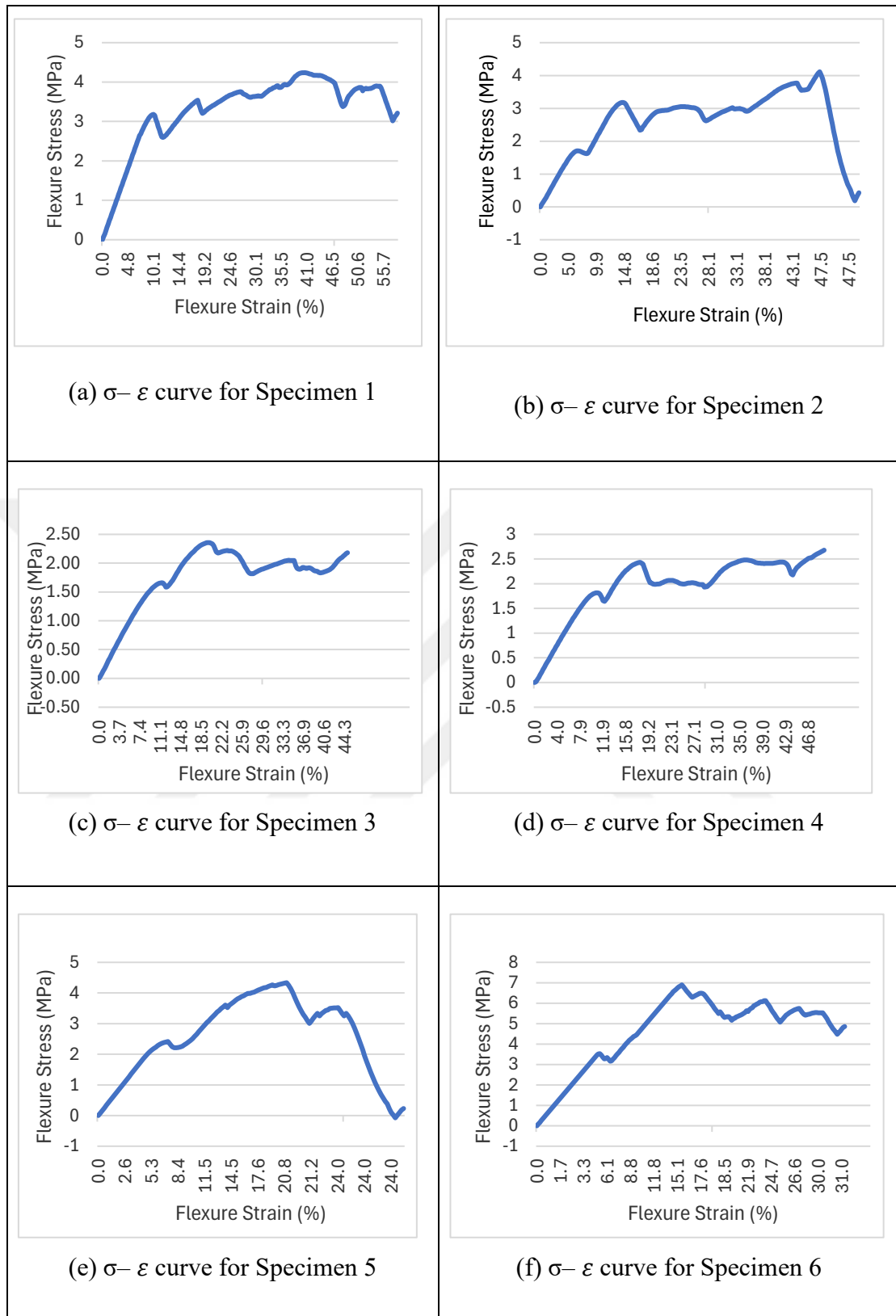


Figure 3.2: (a)–(f). individual stress–strain curves for specimens 1–6.

The σ – ϵ curves presented in Figure 3.2 series show that the manner in which specimens reach the maximum stress and their post-peak load-carrying characteristics

differ. These differences support the idea that the energy absorption capacity is governed not only by peak values but also by the curve shape.

3.4 Mass-specific Stress and Load-Carrying Efficiency

As emphasized, normalizing maximum stress values by mass is critical for assessing design efficiency. In this study, $\sigma_{\max}/m$ was calculated for each specimen and presented in Table 3.1. The $\sigma_{\max}/m$ values ranged between 49.9 and 83.6 MPa/kg; the highest value was obtained for Specimen 6 (≈ 83.6 MPa/kg). Specimens 1, 2, and 5 were in a similar band (≈ 62 – 64 MPa/kg), whereas Specimen 4 yielded the lowest value (≈ 49.9 MPa/kg).

These results show that an increase in absolute load-carrying capacity does not always produce the same level of efficiency increase on a mass basis. Specimen 6 being the leader in both stiffness and $\sigma_{\max}/m$ indicates that this configuration can effectively maintain load-carrying capability even when the mass increase is considered. In contrast, for specimens with low $\sigma_{\max}/m$, a lower nominal stress capacity per unit mass exists, which constitutes a disadvantage in terms of design efficiency.

This subsection should be read together with the normalized metrics in Table 3.1. The purpose here is to evaluate the specimens based on highest $\sigma_{\max}/m$ rather than highest $\sigma_{\max}$ and to provide the requested quantitative interpretation.

3.5 Numerical Validation

To evaluate the numerical model reliability, a direct validation was performed for Specimen 1 by comparing the FEM and experimental reaction force–displacement responses. The comparison was made using the corresponding displacement–reaction force datasets and the overlaid curves shown in the Figure 3.3.

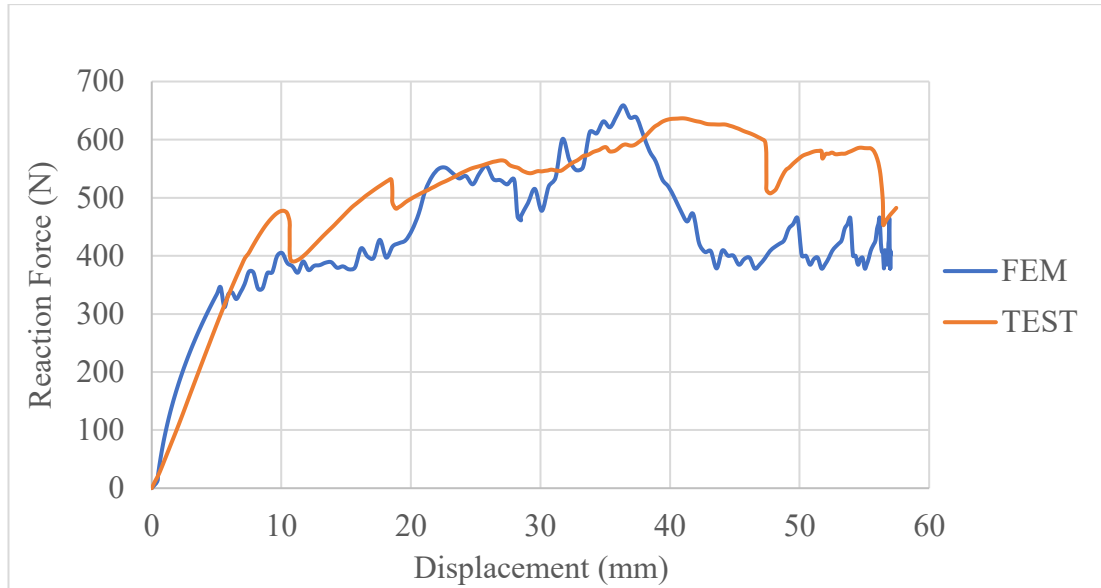


Figure 3.3: Numerical validation of the test for specimen 1.

The comparison shows that the numerical model captures the overall response form of Specimen 1 reasonably well, including the initial load build-up, the progressive increase in force with displacement, and the occurrence of a fluctuating post-peak response. In both curves, the specimen exhibits a non-brittle response with continued load-carrying capacity over a wide displacement range, which indicates that the FEM model successfully represents the general deformation mechanism under three-point bending.

A good agreement is observed in terms of maximum reaction force. The FEM curve reaches a peak load of approximately 659 N, while the experimental curve reaches approximately 637 N, corresponding to a difference of about 3.5%. This close peak-force prediction supports the adequacy of the numerical model in representing the global load-carrying capacity of Specimen 1.

In terms of peak displacement, however, the FEM curve reaches its maximum earlier than the experimental curve. The numerical peak occurs at approximately 36.4 mm, whereas the experimental peak occurs at approximately 40.8 mm. This indicates that the numerical model predicts an earlier development of the dominant local deformation/instability mechanism compared to the test. Nevertheless, despite this shift in peak location, the FEM curve remains within the same force band as the experimental curve over a large portion of the displacement range.

In the initial response region, the FEM curve shows a steeper force increase than the experimental curve, which is consistent with the previously reported stiffness values (numerical k higher than experimental k for Specimen 1). This suggests that the model slightly overestimates the early elastic load-transfer efficiency. After this region, the two curves become closer and show comparable force levels in the mid-displacement range, although the FEM response presents more pronounced oscillations. These oscillations are associated with stepwise local deformation and contact state changes in the numerical model and are consistent with progressive crushing/bending behavior rather than a single catastrophic failure event.

In the post-peak region, both FEM and test curves show continued load carrying with fluctuations, confirming that the response is governed by progressive damage/deformation. However, the FEM curve generally drops to lower force levels than the experiment after the peak and remains more oscillatory. This behavior explains why the numerical Work/kg value is lower than the experimental energy-based metric (E/m), even though the peak force is predicted accurately. In other words, the FEM model reproduces the peak response successfully but underestimates the sustained post-peak load contribution that accumulates energy in the experiment.

Overall, the comparison for Specimen 1 demonstrates that the numerical model provides a satisfactory validation at the global response level, particularly in predicting the maximum load and the general shape of the force–displacement curve. The main differences are the earlier peak occurrence and the lower post-peak force retention in the FEM response. Therefore, for Specimen 1, the FEM model can be considered suitable for comparative interpretation of stiffness and peak load behavior, while some deviation remains in the representation of progressive post-peak energy absorption.

The ratio of kinetic to internal energy remained below 5%, confirming quasi-static conditions and ensuring the reliability of the explicit simulations. To verify quasi-static conditions, internal and kinetic energy histories were monitored. The kinetic energy remained significantly lower than the internal energy throughout the analysis, confirming that inertial effects were negligible.

3.6 Mass-specific Energy Absorption

The energy absorption capacity E was obtained by numerical integration of the area under the load–displacement curve. The absolute energy values varied among specimens, and the highest energy was obtained for Specimen 1 ($E \approx 28.756$ J). However, the key quantity for design efficiency was the mass-normalized energy absorption capacity E/m . The E/m values ranged between 149.6 and 437.0 J/kg, and the highest value was again obtained for Specimen 1 (≈ 437.0 J/kg). Specimens 2–3–4–6 were in the ≈ 281 – 310 J/kg band, whereas Specimen 5 exhibited a clearly lowest E/m (≈ 149.6 J/kg).

This finding indicates that energy absorption cannot be explained solely by stiffness or maximum load. The low energy efficiency of Specimen 5, despite its relatively high stiffness suggests that the continuity of load carrying in the post-peak region may be limited. Conversely, the high E/m performance of Specimen 1 is consistent with maintaining meaningful load levels over a wider deformation interval and thus increasing the area under the curve. Therefore, the curve shape is critical in energy absorption evaluation.

The comparison of the areas under the curves in Figure 3.1 demonstrates that energy absorption is governed not only by peak load but also by the continuity of load carrying during the loading process.

At minimum, an area comparison for Specimen 1, Specimen 5, and Specimen 6 provides a strong narrative.

For the energy-related response, the numerical work/kg values were lower than the experimentally obtained E/m values for all specimens. Nevertheless, the FEM results still support the main experimental tendency that Specimen 1 has the best mass-specific energy absorption performance among the compared configurations. In the numerical results, Specimen 1 gave the highest Work/kg value (199.8 J/kg), while Specimen 6 followed with 159.0 J/kg. This is consistent with the experimental interpretation that Specimen 1 combines favorable deformation progression with strong load-carrying behavior, and that Specimen 6 provides high strength but not the highest mass-specific energy efficiency.

3.7 Deformation Mechanisms

To explain quantitative metrics mechanistically, evaluation of deformation shapes is necessary. In this context, the deformation behavior was compared based on images to be presented at the same displacement level. Thus, the uncertainty that could arise from comparing specimens at different displacement levels at their own peak loads was reduced, and the mechanism comparison was placed on a consistent basis.

The contribution of deformation images to the discussion should be addressed at two levels: Global bending shape and the spread of core deformation defined like in specimens with high E/m , deformation is expected to spread over a wider region and progress via a progressive mechanism, which increases energy dissipation and enlarges the area under the curve, localized crushing/concentration zones and maintenance of load carrying is in specimens with high stiffness and high $\sigma_{\max}/m$, load transfer is expected to be maintained more effectively at the same displacement and local instability is expected to progress in a more controlled manner.

Within this framework, Specimen 6 being the leader in stiffness and $\sigma_{\max}/m$ should be interpreted consistently with a more load bearing deformation character at the same displacement. Specimen 1 being superior in E/m should be associated with a more distributed deformation mechanism favorable for energy absorption.

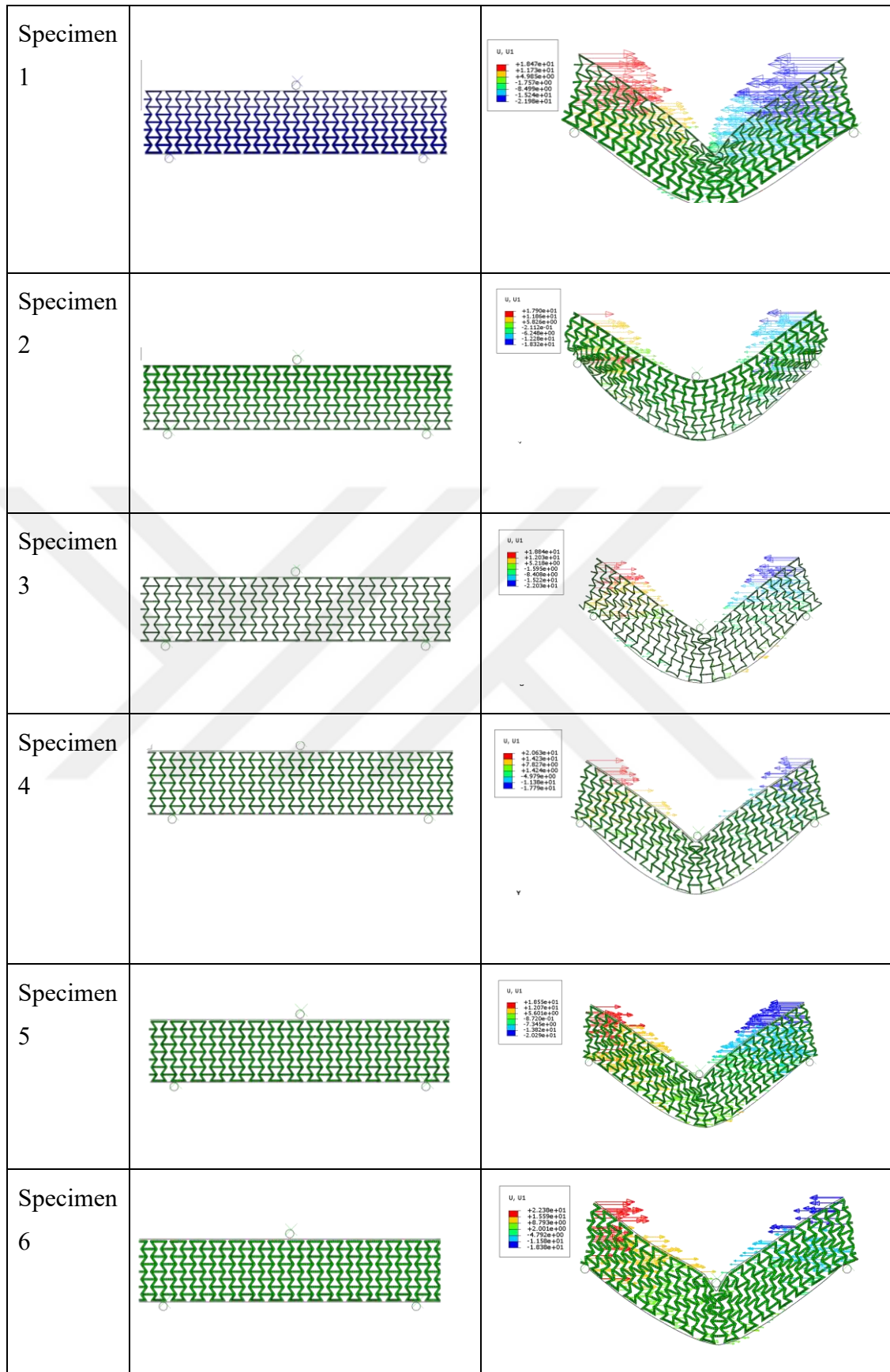


Figure 3.4: Global deformation shapes of all specimens at maximum displacement.

The front cross-sectional images in Figure 3.4 and Figure 3.5 directly reveal the crushing/closure mechanism of the core cells and, in particular, illustrate how the progressive crushing behavior associated with E/m differs among specimens. Whereas a more distributed closure is observed across the section in Specimen 1, the crushing in Specimen 6 is observed to be more confined to a limited region.

Under three-point bending, the deformation of sandwich beams with auxetic (re-entrant) cores is not limited to the global flexural response of the beam; it also evolves through the rotation of the re-entrant cells and the associated inward collapse mechanism. In this mechanism, the cell ribs rotate under loading and reduce the re-entrant angles, so the cells tend to contract and fold inward rather than expand outward. Consequently, as deformation progresses, a global deflection profile develops at the structural scale, while the core-cell geometry is progressively reconfigured, with deformation becoming more pronounced in certain regions.

To present the deformation mechanisms more clearly, the longitudinal displacement component along the beam was visualized on the deformed configurations using vector arrows. The arrow direction indicates the direction of displacement, whereas the arrow color scale represents the graded magnitude of this displacement component (standard FEM vector plot representation). Examination of the plots shows that, for all specimens, vectors on the left half are predominantly directed to the right, while vectors on the right half are predominantly directed to the left, meaning that the motion on both sides is oriented toward the mid-span region. This opposing directionality is consistent with a gathering behavior of the core under bending, for instance, a tendency to move from both sides toward the center and it qualitatively supports the expected inward collapse mechanism of re-entrant auxetic cells. Moreover, the color scale indicates that this longitudinal gathering is more intense in specific zones, implying that the extent of cell rotation and local deformation varies spatially and differs between specimens.

Although inward collapse is observed in all designs, the spatial distribution and degree of localization of deformation differ among specimens. In some specimens, deformation is more clearly localized, with a folding developing near the mid-span region; in others, bending exhibits a more distributed character and is more evenly spread along the core. Specimens with the thinnest cell walls tend to exhibit local instability or buckling at earlier stages of loading, which leads to a less uniform

distribution of vector magnitudes. By contrast, specimens with moderate to thicker cell walls generally display a more symmetric and stable deformation pattern, with the inward collapse mechanism operating in a more consistent manner. These observations indicate that cell wall thickness controls not only the load-carrying capacity of the structure, but also the transmission of cell rotation throughout the core, the overall stability of the deformation process, and the regions in which damage is more likely to localize.



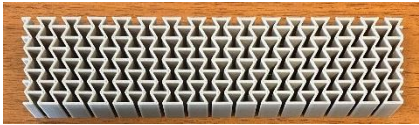
Specimen 1		
Specimen 2		
Specimen 3		
Specimen 4		
Specimen 5		
Specimen 6		

Figure 3.5: Deformation mechanisms of test specimens.

All specimens initially possess a uniform auxetic core configuration prior to loading, which ensures comparable boundary conditions at the onset of the bending tests. After the completion of the bending experiments, however, distinct deformation mechanisms become evident, primarily influenced by the distribution of cell wall thickness across the thickness of each specimen.

Specimen 1 is characterized by a gradual increase in cell wall thickness from the top layer (0.5 mm) to the bottom layer (1.25 mm). In this configuration, deformation is predominantly concentrated in the upper region of the core directly beneath the applied load. The thinner cell walls near the top undergo hinging and rotational deformation at early stages, whereas the thicker layers in the lower part of the core act as a restraining region, limiting the propagation of deformation through the structure. This graded arrangement promotes damage localization while preserving the structural stability of the lower core layers.

In contrast, Specimen 2 exhibits a decrease in cell wall thickness from the top layer to the bottom layer (1.25–0.5 mm), which leads to more pronounced deformation extending into the lower regions of the core. The thinner cell walls in the bottom layers are more susceptible to bending and rotational deformation, resulting in a broader deformation zone and a reduced resistance to the propagation of deformation. Consequently, this configuration provides less effective damage confinement when compared with Specimen 1.

Specimens with uniform cell wall thickness, corresponding to specimens 3–6, exhibit deformation behaviors that are strongly governed by the wall thickness. Among these, Scenario 3 with a thickness of 0.5 mm displays the most compliant response, characterized by extensive cell wall rotation and a gradual densification process across a large portion of the core. In this case, deformation is distributed rather than highly localized, indicating enhanced energy absorption through progressive interactions between adjacent cells. As the uniform cell wall thickness increases from Scenario 4 (0.75 mm) to Scenario 6 (1.25 mm), the deformation response becomes increasingly concentrated near the mid-span region. Thicker cell walls delay local buckling and restrict cell rotation, resulting in higher stiffness but reduced deformation spread. Overall, thinner uniform cores favor distributed deformation and energy dissipation, whereas thicker uniform cores promote stiffness-dominated, localized bending behavior.

In conclusion, the expected inward collapse mechanism of the re-entrant auxetic core under bending is confirmed by the displacement vectors on both sides pointing toward mid-span and the increase of this displacement component in particular regions as shown by the color scale. The variations between specimens further show that whether deformation develops in a more distributed or localized manner depends critically on the cell-wall thickness configuration.

3.8 Foam-filled Specimens

In this subsection, the three tests which are repeatedly conducted for the foam-filled design are consolidated into a single representative result set and evaluated accordingly. Since the tests terminated at different maximum displacements, a common displacement limit U^* was defined in order to report the energy absorption capacity in a comparable manner. Here,

$$U^* = \min (U_{\text{end}}) \quad (3.6)$$

was selected, and for the foam-filled series

$$U^* = 40.00 \text{ mm} \quad (3.7)$$

was determined. This approach ensures that the energy calculation for each repeat is performed over the same displacement interval, thereby improving the repeatability and comparability of the energy metrics. In addition, the energy absorbed by each repeat up to its own test end was also reported for information purposes; however, it was treated as a secondary indicator in direct inter-specimen comparisons. All metrics calculated for the foam-filled series are presented in Table 3.3.

Table 3.3: Experimental results for foam-filled specimen.

Group	Foam-filled Specimens
U^* (mm)	40.0
k (N/mm)	77.1
$F_{\max}$ (N)	719.2
$\sigma_{\max}$ (MPa)	5.0
$\varepsilon(\sigma_{\max})$ (%)	36.5
E_0-U^* (J)	19.0
E_0-U_{end} (J)	21.2

The initial flexural stiffness of the foam-filled specimens was obtained as $k = 77.15$ N/mm. This value indicates that the foam contribution significantly increases the global stiffness of the system in the small-displacement regime. In particular, the stiffness increase in the initial region can be associated with the support provided by the foam matrix to the core cell walls prior to the onset of local buckling, as well as with a more controlled progression of cell closure.

In terms of maximum load-carrying capacity, the foam-filled series reached $F_{\max} = 719.2$ N. When compared with the maximum load ranges of Specimens 1–6, this level indicates that the foam contribution can provide a meaningful improvement in load capacity. Nevertheless, maximum load should not be evaluated in isolation; it should be interpreted together with the displacement at which it occurs and the post-peak curve character. For the foam-filled series, the displacement corresponding to the maximum load was $U(F_{\max}) = 41.69$ mm. Reaching the peak load at relatively larger displacement levels indicates a more sustained load-carrying behavior over the course of loading. This trend directly contributes to an increase in the area under the curve and, consequently, to energy absorption capacity.

With respect to maximum nominal flexural stress, the foam-filled series was reported as $\sigma_{\max} = 4.963$ MPa. The nominal strain at which the maximum stress occurs was

obtained as $\varepsilon(\sigma_{\max}) = 36.52\%$. This result indicates that, with foam contribution, the stress increase is distributed over higher strain levels and that a longer load carrying phase develops before reaching the stress peak. Such behavior is typically associated with a more controlled post-peak softening response rather than a sharp peak followed by an abrupt drop, which may be advantageous in terms of energy absorption.

Energy absorption results were reported in two different scopes. Based on the common displacement limit of test, the energy absorption capacity was found to be $E_{0-U^*} = 19.016$ J. A higher scatter for integral based quantities such as energy is expected, because energy encompasses not only the initial region of the curve but all load-carrying regimes throughout loading, and these regimes are more strongly affected by factors such as manufacturing tolerances, foam placement/density, and the spatial distribution of localized deformation. On the other hand, the energy absorbed up to the end of each test was reported as $E_{0-U_{\text{end}}} = 21.183$ J, indicating that energy naturally increases when repeats continue to higher displacements. However, it should be emphasized that, for fair inter-specimen comparisons, the primary comparison metric is E_{0-U^*} .

In order to support the comparative interpretation of the foam-filled design in a transparent and reproducible manner, the response of the foam-filled series was represented by a single mean curve constructed from the repeated tests. Specifically, the load–displacement records were mapped onto a common displacement domain and averaged to obtain a representative response, while the dispersion around the mean was retained as a statistical envelope. The resulting mean load–displacement curve is presented in Figure 3.6, which provides a compact visualization of both the

characteristic response and its repeatability within the considered displacement interval.

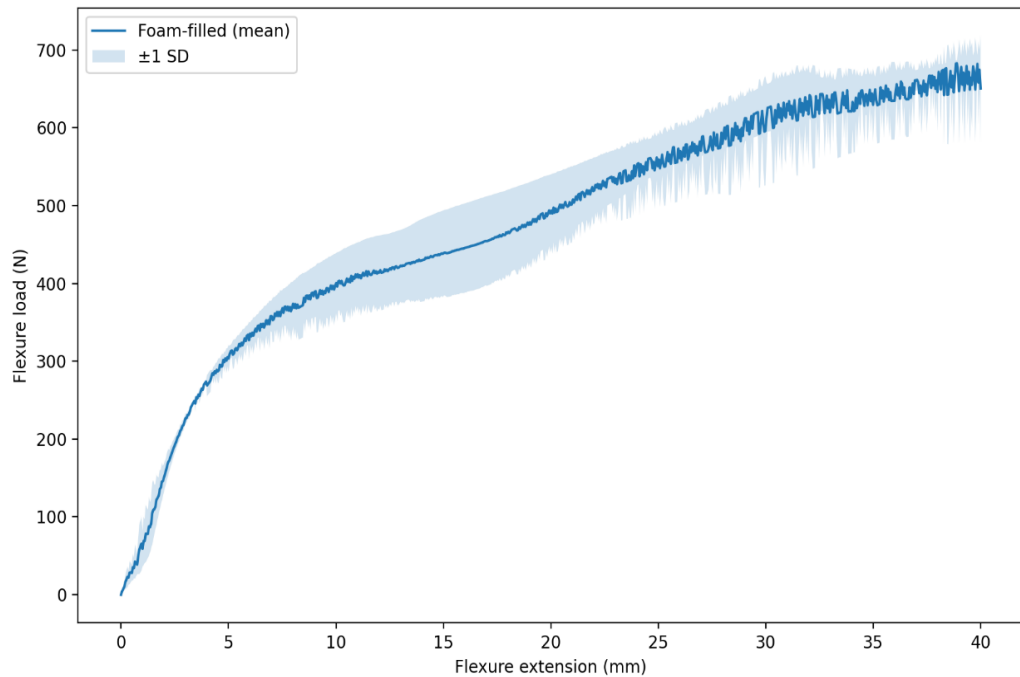


Figure 3.6: Foam mean load displacement.

A direct comparison between the foam-filled configuration and the without foam-filled configuration is provided in Figure 3.7, where the foam-filled mean curve is plotted together with the experimental load–displacement response of Specimens 4 over an identical displacement range.

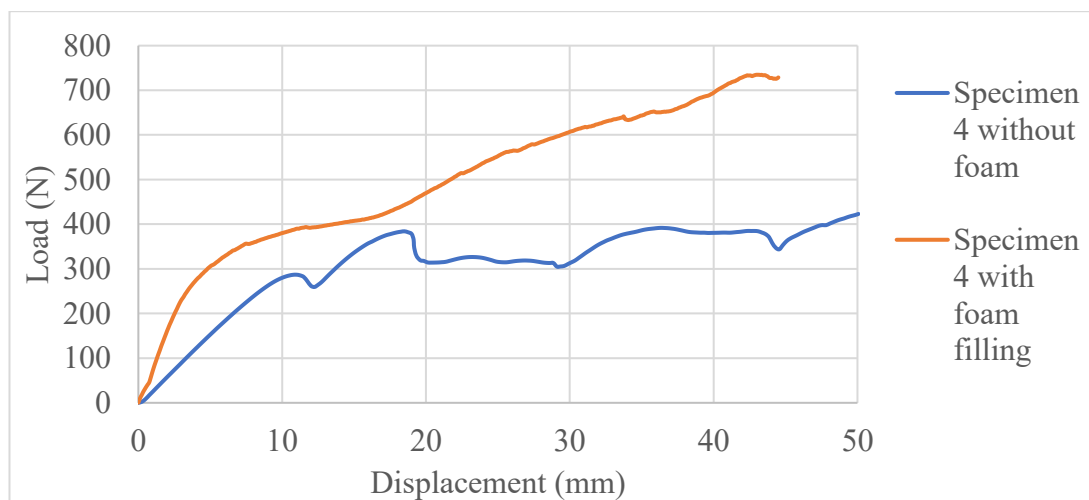


Figure 3.7: Specimen 4 with foam filled vs without foam load-displacement graph.

This representation enables a consistent comparison of the relative flexural stiffness, as reflected by the initial slope, the load-carrying capacity throughout the loading history, and the initiation and progression of post-peak behavior. In particular, the comparative plot facilitates the assessment of whether the presence of foam primarily contributes to an increase in initial stiffness, maintains higher load levels over an extended displacement range or delays load drops associated with localized crushing and stiffness degradation.

To complement the force-based evaluation, the foam-filled configuration was also examined using the nominal stress–strain response derived from the experimental data. The averaged stress–strain curve, obtained using the same averaging procedure applied to the load–displacement results, is presented in Figure 3.8. This figure directly supports the discussion of the relationship between the maximum nominal flexural stress and the corresponding nominal strain. In this way, it provides a clear graphical basis for evaluating whether the foam-filled design promotes a more gradual stress evolution and a smoother post-peak transition when compared with the baseline specimens.

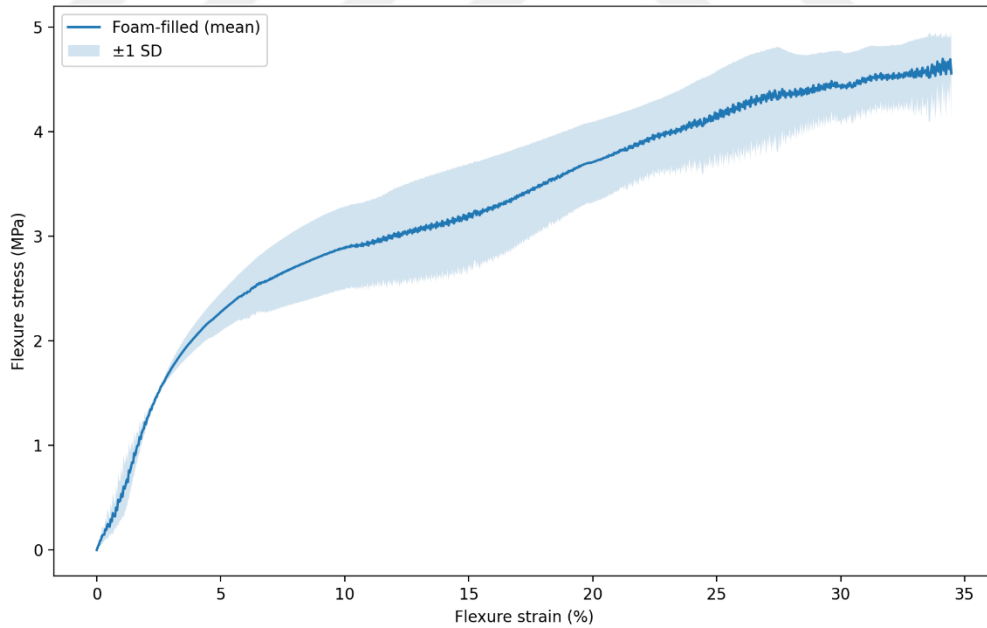


Figure 3.8: Stress-strain response of foam filled specimen.

For completeness and to ensure the traceability of the reported results, the key statistical descriptors of the foam-filled specimen series are summarized in Table .3. Including the initial stiffness k , the maximum load $F_{\max}$, the maximum nominal

flexural stress $\sigma_{\max}$, the strain at maximum stress $\varepsilon(\sigma_{\max})$, and the energy absorption are investigated at the common displacement interval. Table .3 and Figure 3.6, Figure 3.7, and Figure 3.8 provide a set of quantitative and visual evidence that positions the foam-filled configuration relative to specimens 1–6 and supports the interpretation of its flexural performance. It is in terms of stiffness, load carrying capability, and energy absorption characteristics.

When evaluating both the quantitative and qualitative results together, a distinct multi-objective performance distinction appears among the specimens. Specimen 6 demonstrates superior stiffness and mass-specific maximum stress, while Specimen 1 clearly leads in mass-specific energy absorption capacity. This indicates that the definition of the best specimen depends on the target function. If the application requirement is stiffness and load-carrying capability, the evaluation focusing on stiffness and $\sigma_{\max}/m$ becomes prominent; if energy damping/absorption is targeted, E/m becomes a critical determinant. Presenting the deformation and front cross-sectional images standardized at the same displacement will provide a mechanism-based explanation of these quantitative results and will increase the scientific strength of the interpretations.

4. CONCLUSIONS

The research objectives, key findings, practical implications, and suggested future work are all summarized in this chapter, which concludes the thesis.

Research scope and objectives of the research are the current study examining how different core wall-thickness configurations affect initial flexural stiffness, maximum nominal flexural stress, and energy absorption capacity in auxetic re-entrant sandwich beams made with AA1050 face sheets and a PLA re-entrant core. Three-point bending tests for six baseline specimens and finite element simulations created to replicate the experimental setup were used for the evaluation. To evaluate the impact of foam penetration on flexural response at the specimen level, a foam-filled variant was also produced and tested.

As a summary of findings, the results highlight clear performance trade-offs among the six baseline specimens between designs optimized for energy absorption and those prioritizing stiffness and strength. Specimen 6, which exhibited an initial stiffness of 123.47 N/mm, a maximum load of 1023.2 N, and a peak flexural stress of 6.898 MPa, achieved the highest values when absolute stiffness and load-carrying capacity were the primary objectives. In contrast, when energy absorption performance was considered, Specimen 1 demonstrated the highest specific energy absorption, reaching 437.0 J/kg, and absorbed the greatest amount of energy within the examined displacement range, amounting to 28.756 J. This behavior indicates a higher energy absorption efficiency per unit mass, despite lower peak strength values compared with Specimen 6. Overall, these findings confirm that an increase in load-carrying capacity does not necessarily correspond to a maximization of energy absorbed per unit mass, and that the most suitable design strongly depends on the intended application requirements.

The use of specific, mass-normalized performance indicators further clarified these trade-offs. In this context, Specimen 6 exhibited the highest specific stiffness, measured as 1496.6 (N/mm)/kg, along with the highest specific peak stress of 83.61 MPa/kg, underscoring its effectiveness in applications where weight-sensitive stiffness and strength are critical design targets. However, its specific energy absorption (281.5

J/kg) remained below that of Specimen 1, reinforcing that the most stiffness/strength-efficient configuration is not automatically the most energy-efficient configuration. In addition, the baseline experimental results support the thesis premise that wall-thickness configuration of re-entrant auxetic cores can be tuned to shift performance toward either high stiffness/strength or high energy absorption efficiency, depending on the design intent.

The foam-filled configuration was evaluated experimentally using three repeat tests consolidated into a single representative response. The foam-filled specimens achieved a mean initial stiffness of 77.15 N/mm and a mean maximum load of 719.2 N, placing the foam-filled response above most baseline specimens in stiffness and load capacity while remaining below the strongest baseline case (Specimen 6). The maximum nominal flexural stress of the foam-filled configuration (4.963 MPa) also exceeded the peak stress levels of several baseline specimens, indicating that foam infiltration can enhance stress-carrying capability under bending.

For energy absorption, the foam-filled tests terminated at different maximum displacements; therefore, energy was reported both up to the common displacement limit and up to each test's end displacement. Although the foam-filled configuration did not reach the full displacement range used as a reference for Specimens 1–6, the amount of energy absorbed over the shorter displacement interval indicates that foam infiltration helps sustain load-carrying capacity over a considerable portion of the deformation process. This observation supports the use of foam infiltration as a practical strategy for improving flexural robustness without relying solely on an increase in core wall thickness.

The synthesis of experimental and numerical assessments can be expressed like the finite element simulations developed for Specimens 1–6 provided additional insight into the bending response, with particular emphasis on the underlying deformation mechanisms and overall behavioral trends. In particular, the numerical results supported the qualitative interpretation of progressive core deformation and load transfer through the face sheets and auxetic core architecture. At the same time, the comparison highlighted that quantitative accuracy is sensitive to modelling choices (e.g., contact representation, material calibration, and damage/softening description), which is consistent with the general expectation that FE models of architected polymers under large deformation require careful calibration to match experimentally

observed force levels and absorbed energy. As a result, within the scope of this thesis, the FE work is best interpreted as a mechanism- and trend-supporting tool for the baseline set, while the experimental results remain the primary source for quantitative performance statements.

From an engineering design perspective, the study provides actionable guidance for selecting re-entrant auxetic core configurations under flexural loading. If peak strength and stiffness are dominant objectives, the best-performing baseline configuration (Specimen 6) demonstrates that higher stiffness/strength can be achieved, including superior mass-normalized stiffness and peak stress. If energy absorption efficiency is dominant, the best-performing energy-efficient configuration (Specimen 1) demonstrates that maximizing absorbed energy per unit mass may require different thickness strategies than those that maximize peak force or stiffness. If balanced performance is required, the foam-filled approach offers a feasible route to elevate stiffness and load capacity relative to many baseline configurations while maintaining substantial energy absorption over the attainable displacement window.

These conclusions collectively support the thesis contribution. Re-entrant auxetic sandwich beams can be systematically tuned through wall-thickness configuration and foam infiltration to meet different performance targets under bending.

As recommendations for future work, it is consistent with common expectations for thesis conclusions, the following directions are recommended to extend the present work and strengthen the generality of the findings.

Multi-objective design optimization can be done. Extend the specimen matrix to explore additional thickness gradients and intermediate configurations, and apply multi-objective optimization (e.g., maximize (E/m) while constraining stiffness and stress).

Foam parameter study can be done. Investigate foam density, filling ratio, and foam–polymer interaction to identify the regimes where foam improves load stability without excessive mass increase.

Enhanced constitutive and damage modelling can be developed. Incorporate polymer nonlinearity and progressive damage/softening calibrated directly from coupon tests and/or inverse identification to improve quantitative FE agreement.

Manufacturing variability and defect sensitivity can be an another option. Quantify geometric imperfections (wall-thickness tolerances, bonding quality, voids) and propagate them into uncertainty bounds on stiffness, peak stress, and energy absorption.

Rate and cyclic effects can be studied. Evaluate loading-rate sensitivity and repeat/cyclic bending to determine whether the preferred configuration changes under dynamic or fatigue-relevant conditions.

In conclusion, this thesis showed that the flexural behavior of re-entrant auxetic sandwich beams is largely influenced by the core wall-thickness setup and can be adjusted through foam infiltration. The experimental results provided clear and quantitative rankings with respect to stiffness, peak stress, and energy absorption, including mass-normalized performance indicators. In parallel, finite element modeling supported the interpretation of deformation mechanisms and general behavioral trends observed in the baseline specimens. Taken together, these findings establish a robust basis for the selection and tailoring of auxetic sandwich beam designs for applications in which stiffness, strength, or energy absorption represent the primary performance requirements.

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BIOGRAPHY

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