

A COMPREHENSIVE REVIEW OF THE RECENT DEVELOPMENTS IN THE MECHANICS OF SANDWICH PANELS WITH AUXETIC METAMATERIAL CORES

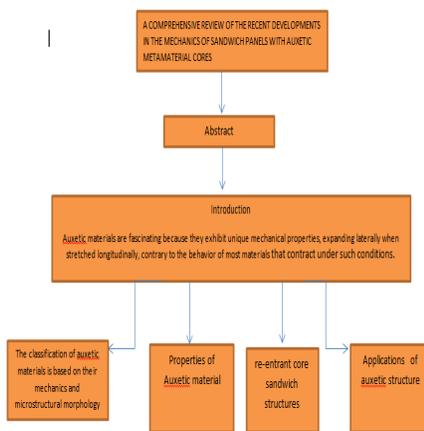
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Graphical abstract



Abstract

Auxetic materials are engineered structures characterized by a negative Poisson's ratio, enabling lateral expansion under tensile loading. This unconventional deformation mechanism enhances structural stability, impact resistance, and energy absorption, making auxetic configurations attractive for lightweight sandwich structures used in advanced engineering applications. However, despite their promising behavior, the practical utilization of auxetic-core sandwich panels remains limited due to insufficient quantitative understanding of their response under bending, compression, and dynamic loading. In addition, challenges related to geometric optimization and scalable manufacturing techniques restrict broader implementation. This review provides a systematic quantitative assessment of sandwich panels incorporating auxetic cores, based on experimental, analytical, and numerical studies reported in the literature. Comparative results indicate that auxetic-core sandwich structures can enhance energy absorption capacity by approximately 30–60% and improve impact resistance by 25–40% relative to conventional positive Poisson's ratio honeycomb cores, depending on core topology and material selection. Furthermore, additive manufacturing technologies, particularly 3D printing, enable precise fabrication of complex re-entrant geometries, contributing to measurable improvements in stiffness-to-weight ratio and dynamic performance. Overall, the compiled quantitative evidence confirms that optimized auxetic core geometries can significantly enhance mechanical efficiency and load resistance in sandwich structures. These findings demonstrate the strong potential of auxetic-based designs for aerospace, automotive, and protective structural applications, while highlighting the need for further research on hybrid architectures and scalable manufacturing strategies.

Keywords: Auxetic Materials, Auxetic Sandwich Structures, Negative Poisson's Ratio (NPR), Mechanical Behavior, Metamaterials

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1.0 INTRODUCTION

Auxetic materials are a unique class of materials that exhibit a negative Poisson's ratio, meaning they expand laterally when stretched rather than contracting like conventional materials. As shown in Figure 1. This distinctive property provides auxetic materials with unprecedented mechanical advantages, such as improved impact resistance, enhanced energy absorption capacity, and increased fracture toughness and fatigue resistance. Due to these exceptional characteristics, auxetic materials have gained increasing interest in various engineering applications, including aerospace, automotive, ballistic armor, medical devices, and smart structures. Historically, the concept of materials with a negative Poisson's ratio was first documented by Love in 1944 [1], but a deep understanding of these materials only began to emerge decades later. In 1982, Gibson discovered the auxetic effect in two-dimensional structures using aluminum honeycomb and silicone rubber [2, 3]. The most significant breakthrough came in 1987 when Lakes successfully fabricated the first synthetic auxetic material, paving the way for extensive research into this phenomenon [5–4]. Despite the fact that auxetic materials have been known for over a century, significant scientific and practical interest only emerged in the late 1980s as the demand for advanced materials with enhanced mechanical properties increased. The behavior of auxetic materials is closely linked to their microstructure and deformation mechanisms, where the negative Poisson's ratio arises from the internal structural arrangement and interaction under mechanical loads [6–12]. Researchers have classified auxetic behavior into four main categories: non-auxetic, slightly auxetic, auxetic, and fully auxetic [13–15]. Over time, research has expanded to encompass new types of auxetic materials, including polymers, metals, ceramics, and advanced composites. Despite significant advancements in the study of auxetic materials, many research gaps remain, making this review highly relevant in the engineering field. This study aims to provide a comprehensive analysis of different types of auxetic cores, extending beyond conventional re-entrant and chiral structures to include graded, hybrid, hierarchical, and two-dimensional and three-dimensional auxetic structures. This broader scope enhances the understanding of how geometric design influences mechanical properties, an aspect that has not been thoroughly explored in previous studies. Furthermore, this review highlights modern manufacturing techniques, particularly additive manufacturing and 3D printing, discussing how these methods can improve the precision and quality of auxetic material production, enhance impact response, and enable complex designs that were previously unachievable with traditional manufacturing techniques [16, 17, 18]. Additionally, the study provides an in-depth analysis of the effects

of auxetic structures on impact resistance and energy absorption, investigating their potential to enhance penetration resistance and energy dissipation in defense and military applications, such as ballistic armor, blast-resistant panels, and impact protection for vehicles and aircraft [19, 20, 21, 22, 23]. Moreover, this review explores critical mechanical properties such as fracture toughness and fatigue resistance, areas that have not been sufficiently addressed in previous research. By analyzing the relationship between the negative Poisson's ratio and the ability of materials to withstand long-term mechanical loading, this study sheds light on fracture resistance, fatigue behavior, and their significance in applications requiring high durability, such as space structures and biomedical engineering [24, 25, 26, 27, 28, 29]. Furthermore, this review presents a forward-looking perspective by identifying research gaps and proposing future research directions, such as developing environmentally friendly auxetic materials, incorporating natural fibers into auxetic structures, and examining the effects of random cell arrangements on mechanical performance instead of relying solely on idealized geometric patterns [30, 31, 32, 33, 34, 35].

There are four sections in this review:

- **Mechanical Properties:** The mechanical characteristics of auxetic structures are covered in this section, with an emphasis on energy absorption, strength, flexibility, and toughness.
 - **Auxetic structure classification:** Based on their mechanics and microstructural morphology, auxetic materials are categorized in the second section. Three common types are highlighted, with particular attention paid to the re-entrant auxetic structure type, as this is the type from which the samples used in the current study were made.
 - **Applications:** The various uses of auxetic structures in various sectors are examined in this section. Their applications in biomedicine, military vehicles, automotive, aerospace, sensors, motors, and textiles are a few examples.
 - **Sandwich structures with re-entrant cores:** This section examines the significance of auxetic cores on sandwich panel structures in terms of resilience, strength, and energy absorption.

This study aims to provide a comprehensive review that integrates auxetic core design, advanced manufacturing techniques, in-depth mechanical property analysis, and practical applications. By focusing on recent technological developments and unexplored aspects in previous studies, this review serves as a valuable reference for researchers seeking to develop smarter and more efficient materials for modern industries. This work opens new avenues for utilizing auxetic materials in advanced industrial and engineering applications, highlighting their potential as next-generation materials for diverse technological fields.

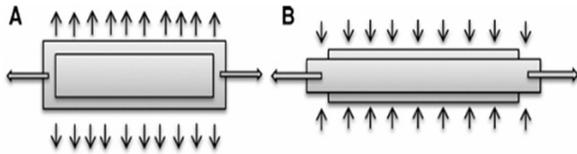


Figure 1 compares the auxetic and non-auxetic behavior of numerous materials. With (A) denoting auxetic activity and (B) denoting non-auxetic behavior, [7]

2.0 AUXETIC STRUCTURES

Different classifications of auxetic materials are analyzed, such as re-entrant honeycombs, chiral honeycombs, and perforated auxetic structures. It also discusses how these structures are designed to achieve the desired mechanical performance, along with examples of their applications in modern industries.

The word "auxetic" describes a material's ability to thicken when stretched in a single direction, a phenomenon called axial stretching. In his research, Voigt observed that iron pyrite crystals expanded laterally when stretched. However, he could not explain this unusual behavior. Until 1944, when Love discussed materials with NPR, this phenomena was largely ignored [36, 37]. Gibson used NPR to describe the flexure of the ribs as part of the 1982 deformation process of 2D silicon rubber and aluminum honeycomb. Almgren constructed the first building with a negative Poisson's ratio in 1985. This construction was constructed using hinges and springs, as seen in Figure 2.

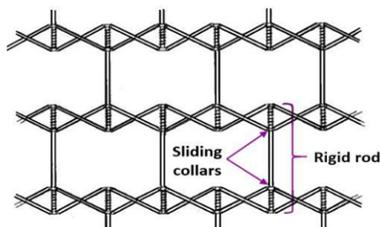


Figure 2 A simple structure with non-proportional response (NPR) produced by hinges and springs [38]

Lakes' work in 1987 marked the beginning of the creation and broad recognition of structures with NPR [39]. By transforming standard foam through several manufacturing processes, Lakes produced a re-entrant foam that demonstrated isotropic NPR in three primary directions in a work published in Science [39, 40]. The manufacturing procedure to convert conventional foam (Figure 3a) into re-entrant foam (Figure 3b) was described in detail in later experimental work conducted by Friis *et al.* in 1988 [41]. According to Lakes [42], the recently created re-

entrant foam was more resilient and robust than traditional foam. Lakes and Friis *et al.*'s work was noteworthy since it demonstrated experimentally how to use NPR to transform conventional foam into auxetic foam.

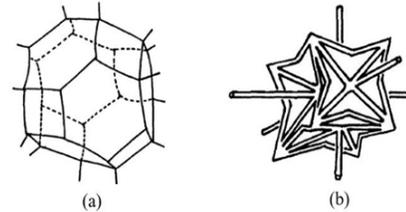


Figure 3 shows idealized foam unit cells: (a) re-entrant foam; (b) typical foam [41]

Materials having NPR attracted a lot of interest from academics when Lakes' study was published. In their research, Evans and Caddock used NPR to examine the microstructure and deformation mechanisms of materials [43–45]. Due to the micro-rotation of the material's microporous network, they found that some microporous polytetrafluoroethylene (PTFE) displayed significant NPR under tensile loadings [46, 47]. Then, in order to create NPR foam, Choi *et al.* [48] and Chan *et al.* [49] created a standard manufacturing procedure (thermo-mechanical process). By laminating unidirectional tapes with alternating plies at angles $\pm\theta$ with respect to a reference direction, Clark *et al.* created composite panels [50,51]. The NPR values were between 15° and 30°, with the angles ranging from 0° to 40°. Although it was difficult to regulate the qualities of the foams that were created, the thermo-mechanical approach emerged as the most popular technique for creating polymer and metallic foams with NPR [52, 53]. Numerous structural auxetics made of metals, polymers, composites, ceramics, and laminates were produced as a result of improvements in conventional production techniques [54–61]. In his research on modified auxetic honeycombs, also referred to as re-entrant honeycombs, and standard hexagonal honeycombs, Evans coined the term "auxetic" [62]. The geometries and physical reactions of auxetic and conventional honeycombs under stretching are depicted in Figure 4. The angle of the slanted walls is the main difference between the two forms of honeycomb. The re-entrant honeycomb differs from traditional honeycombs in that it has an angle between the inclined and vertical walls, which results in outward and inward movements under tension and compression, respectively. Later advancements produced a number of topologies based on the re-entrant honeycomb's deformation mechanism [63–70], with the goal of enhancing mechanical performance to meet increasingly stringent technical specifications.

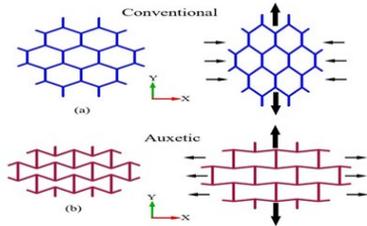


Figure 4 The diagram illustrates two variations of honeycombs and their respective reactions when subjected to axial stretching. (a) a traditional hexagonal honeycomb and (b) an auxetic re-entrant honeycomb [67]

3.0 AUXETIC MATERIALS ARE CATEGORIZED ACCORDING TO THEIR MICROSTRUCTURAL MORPHOLOGY AND MECHANICS

Auxetic materials are classified into several categories according to their microstructure and the way they respond to mechanical stresses, with a focus on the unique properties of each type. It also discusses how the geometric design affects the ultimate performance of these materials.

3.1 Re-entrant Honeycombs

In 1982, Gibson *et al.* introduced the re-entrant honeycomb structure [71], which represents the earliest known example of an auxetic honeycomb with regular unit cells. Figures 6(a) and 6(b) illustrate the unit cells of a 2D re-entrant honeycomb and a conventional hexagonal honeycomb, respectively. The primary distinction lies in the angle between the inclined and vertical walls: for the conventional hexagonal honeycomb, this angle exceeds 90°, whereas for the re-entrant honeycomb, it is less than 90°. The re-entrant honeycomb displays auxetic behavior when subjected to axial tension due to the rotation of hinged joints at the intersections of the vertical and inclined walls. The simple design and significant negative Poisson's ratio (NPR) of the re-entrant auxetic honeycomb have made it a focal point in research [72–78]. Masters *et al.* [79] conducted a theoretical investigation into the deformation mechanisms of both auxetic and conventional honeycombs, deriving their Poisson's ratios and Young's moduli. Figure 5 illustrates the geometric parameters relevant to these analyses.

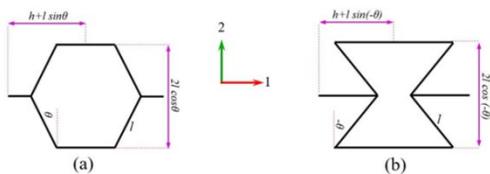


Figure 5 shows (a) a re-entrant honeycomb unit cell and (b) a typical hexagonal honeycomb unit cell [79]

Hui *et al.* [80] employed a large-deformation theoretical approach to predict the Poisson's ratio of a 2D re-entrant honeycomb under substantial deformation. The predicted Poisson's ratios for loading in the X and Y directions, with the geometric characteristics illustrated in Figure 6. Their analysis revealed that the estimated negative Poisson's ratio (NPR) of a 2D re-entrant honeycomb under large deformation exhibited significant variation with strain, as depicted in Figure 7.

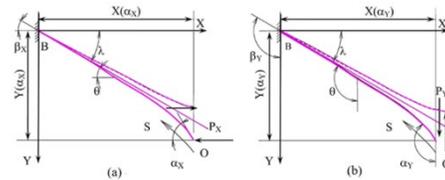


Figure 6 Deformation of the half-inclined member along the: (a) X direction, (b) Y direction. (The deformations caused by remote compressive and tensile stresses are represented by the structures and dashed lines, respectively [80])

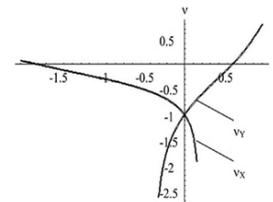


Figure 7 shows how the assumption of significant deformation affects the predicted Poisson's ratio of a 2D re-entrant honeycomb [80]

Building on the concept of 2D re-entrant honeycombs, researchers developed 3D re-entrant structures. In 1994, Evans *et al.* introduced the first 3D re-entrant structure by altering the unit cell of an open-celled foam, as illustrated in Figure 8a [81]. Subsequently, Yang *et al.* [82] investigated the mechanical properties of 3D re-entrant structures through both experimental and theoretical approaches. Figure 8b depicts a 3D unit cell used to fabricate 3D re-entrant specimens. Their findings revealed that the mechanical behavior of 3D re-entrant structures was highly dependent on the geometric attributes of the unit cells, such as strut length, strut ratio, and re-entrant angle.

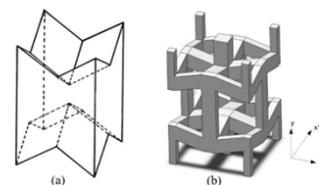


Figure 8 (a) An elongated dodecahedron in three dimensions; (b) A 3D re-entrant structure's unit cell [82]

Xue *et al.* [83, 84, 85] proposed a 3D re-entrant structure featuring cylindrical struts, created by linking 2D re-entrant unit cells. The fabrication process involved 3D printing resin patterns, which were placed inside a stainless steel container filled with plaster slurry. Once the plaster dried, the setup was heated to burn out the resin patterns. Molten aluminum was then poured into the plaster molds. After cooling and setting, the plaster molds were removed by spraying water, leaving behind the aluminum 3D re-entrant structure with cylindrical struts, as illustrated in Figure 9 [82].

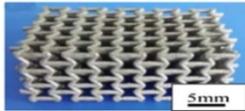


Figure 9 An investment casting and 3D printed aluminum re-entrant auxetic structure [82]

3.2 Chiral Honeycombs

The wrapping or unwrapping ligaments around cylinders are one example of another deformation mechanism that might produce auxetic behavior. Researchers have shown a great deal of interest in chiral honeycombs, another novel class of auxetic structures [86, 87–94]. A chiral honeycomb is made up of cylinders, also called nodes, in its unit cell that are connected tangentially by straight ligaments, also called ribs. A typical chiral honeycomb has a Poisson's ratio of around -1, as determined by both theoretical and experimental studies [95].

There are two main types of chiral honeycombs: chiral and anti-chiral [96, 97, 98]. As seen in Figures 10a, c, and e, a chiral topology has adjacent cylinders positioned on opposing sides of the linking ligaments. However, adjacent cylinders on the same side of the connecting ligaments define an anti-chiral topology (Figures 10b and d). In each topology, the number of ligaments connected to each cylinder determines the various types of connecting systems. These linking systems fall into three-, four-, and six-coordinated ligaments, respectively, and are categorized as trichiral, tetrachiral, and hexachiral structures [98]. The bending of ligaments brought on by the rotation of cylinders in reaction to external forces is a component of the deformation process of chiral honeycombs with 3, 4, and 6 coordination, according to Alderson *et al.* [97].

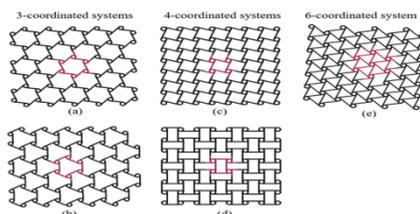


Figure 10 Hexachiral, trichiral, anti-trichiral, tetrachiral, and antitetrachiral chiral structures [93]

The transformation of 2D chiral honeycombs into 3D chiral structures has been explored through various design approaches. Fu *et al.* [99] developed an innovative 3D chiral structure based on the topology of a 2D tetrachiral design. As depicted in Figure 19, 2D tetrachiral units were systematically arranged along the X, Y, and Z axes to form a 3D unit cell. Additionally, Wu *et al.* [100], Xia *et al.* [101], and Farrugia *et al.* [102–104] contributed to the advancement of 3D chiral structures by replacing the cylinders in 2D auxetics with solid cubes. Fu *et al.* [105] also introduced two variants of 3D chiral structures derived from the 2D tetrachiral topology, including one with square loops (SL).

3.3 Perforated Auxetic Structures

Perforated structures represent another class of auxetic designs, created by introducing random or specific cuts into a sheet, forming rectangular spaces that generate a negative Poisson's ratio (NPR) when subjected to in-plane stretching or compression. Shan *et al.* [108] investigated the mechanical properties of a 2D elastomeric sheet featuring elongated periodic cuts, as shown in Figure 11. Their combined experimental and analytical study demonstrated that modifying the shape of the cuts could influence the auxetic behavior. Among the five cut patterns examined, those with three- and six-fold symmetry exhibited isotropic mechanical responses.

Grima *et al.* [106] extended this concept by proposing perforated auxetic structures with random cuts. Despite the irregularity of the incisions, their numerical and experimental analyses confirmed that these structures exhibited NPR behavior. Additionally, Tang *et al.* [107] conducted a comprehensive study on the mechanical behavior of a novel auxetic structure, employing experimental, computational, and analytical methods. Their findings revealed that integrating hierarchical topology with kirigami-inspired designs (featuring line cuts and cutouts) could enhance stretchability and compressibility.

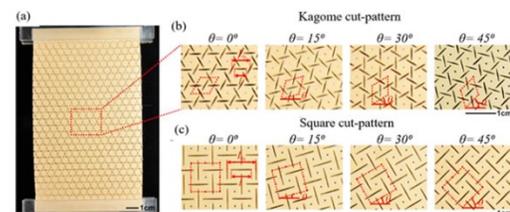


Figure 11 (a) A photograph displaying a specimen featuring a kagome cut pattern; (b) magnified views of the central region of specimens exhibiting various angles (θ) of the kagome cut pattern; (c) magnified views of the central area of specimens showcasing different angles (θ) of the square cut pattern [108]

4.0 PROPERTIES OF AUXETIC MATERIAL

The key mechanical properties of auxetic materials, are analyzed. It is also explained how these properties

can contribute to improving the performance of materials in practical applications such as armor and space structures. where Auxetics offer a promising alternative for various applications due to their distinctive deformation behavior, which imparts exceptional mechanical properties. Key attributes include significantly enhanced energy absorption, increased shear modulus, improved fracture toughness, adjustable permeability, and heightened resistance to indentation. These unique characteristics make auxetics highly suitable for specialized engineering and industrial applications.

4.1 Bulk and Shear Moduli

Enhancements in the mechanical properties of auxetic structures are supported by classical elasticity theory [109]. The four primary elastic constants that define a material's mechanical behavior are Poisson's ratio (ν), shear modulus (G), bulk modulus (K), and Young's modulus (E) [110, 111]. These constants play a crucial role in characterizing and predicting the performance of auxetic materials under various loading conditions, as in the following Equations (1) and (2) [112]:

$$G = \frac{E}{2(1 + \nu)} \dots \dots (1)$$

$$K = \frac{E}{3(1 - 2\nu)} \dots \dots (2)$$

The Equations (1) and (2) defining the relationship between Poisson's ratio (ν), shear modulus (G), and bulk modulus (K) highlight how variations in Poisson's ratio affect these moduli without altering the Young's modulus (E). For example, as ν decreases to negative values, and when G and E are approximately equal, the material exhibits enhanced resistance to shear. Specifically, when $\nu = -0.5$, the shear and Young's moduli are equal. As Poisson's ratio decreases further below -0.5 , the shear modulus becomes significantly larger than both the bulk modulus and Young's modulus ($G \gg E$ and K). This indicates that materials with a negative Poisson's ratio are highly resistant to shear deformation while being easily deformable volumetrically .

On the other hand, rubber-like materials behave oppositely. As ν approaches 0.5, the bulk modulus (K) tends toward infinity, making these materials highly resistant to volumetric deformation while remaining relatively easy to shear. This contrast underscores the unique mechanical properties of materials with varying Poisson's ratios [113].

4.2 Indentation Resistance

Compared to traditional structures constructed from the same parent materials, auxetic structures exhibit noticeably superior penetrating resistance. Non-auxetic structures flow away from the indentation area when they are indented, which lowers the

density beneath the indenter and, as a result, the indentation resistance (Figure 12(a)) [114]. On the other hand, when an auxetic structure is indented, it shrinks laterally, which increases the local density and allows material to flow into the indentation area (Figure 12(b)). The classical theory of elasticity, which links a material's hardness to its resistance to penetration, can be used to explain this variation in indentation resistance, as in the Equation (3):

$$H = \left[\frac{E}{(1 - \nu^2)} \right]^\gamma \dots \dots (3)$$

The parameter γ , which is set to 1 for uniform pressure distribution or frac {2/3} for Hertzian indentation, From Equation (3), it is clear tha the relationship between hardness (or indentation resistance) and Poisson's ratio. Specifically, hardness approaches infinity as Poisson's ratio (ν^2) reaches -1 and its lowest values as approaches 0.5 [115]. Alderson *et al.* conducted experimental studies on the indentation resistance of auxetic ultra-high-molecular-weight polyethylene (UHMWPE) foam [116]. Their findings demonstrated that the indentation resistance of the auxetic foam was significantly higher than that of a comparable conventional foam under both static and dynamic loads. Similarly, Durenberger *et al.* [117] employed numerical analysis to examine the elastic properties of auxetic structures using various indentation tests. Their results showed that the auxetic behavior of honeycomb structures had a substantial impact on indentation resistance under specific conditions, outperforming traditional honeycomb structures.

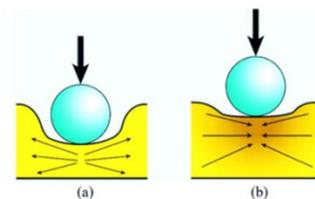


Figure 12 Indentation resistance of conventional and auxetic materials [117]

4.3 Fracture Toughness and Energy Absorption

Auxetic materials exhibit exceptional fracture toughness and energy absorption compared to conventional materials, making them ideal for applications requiring high strength and impact tolerance. Studies indicate that auxetic materials have greater fracture toughness due to their unique structure that reduces the speed of crack propagation. For example, research has shown that the fracture toughness of auxetic polyurethane foam increased by 1.7-3.2 times when different compression ratios were applied [118]. This is due to the self-closing mechanism of cracks within the material, which

enhances its resistance to collapse. In addition, other studies have shown that auxetic materials require more energy to propagate cracks, making them more durable than conventional materials [119, 120]. In addition, auxetic materials have a high energy absorption capacity when subjected to dynamic loads, making them effective in reducing the effects of shocks and vibrations. Experiments have shown that tubes filled with auxetic foam significantly outperform empty or conventional foam-filled tubes in terms of energy absorption efficiency, as shown in Figure 14 [121–122]. Furthermore, studies have shown that auxetic cellular structures, such as double-arrow and inverse-honeycomb cells, provide improved load distribution performance and reduced impact forces, enhancing their potential in defense and engineering applications, such as body armor, spacecraft structures, and automotive shock absorbers [123, 124, 125]. Figure 14 shows a comparison between empty tubes, tubes filled with conventional foam, and tubes filled with auxetic foam in terms of energy absorption capacity (EA) under quasi-static loading conditions (Quasi-Static Loading) where the horizontal axis (X-Axis): represents the types of tubes tested, which are: Empty Square Tubes (EST) Conventional Foam-Filled Square Tubes (CFFST) Auxetic Foam-Filled Square Tubes (AFFST) Vertical axis (Y-Axis): represents the amount of energy absorption (EA) for each type of tube, which is a measure of the material's ability to dissipate energy when exposed to compressive forces or shocks. As a result, tubes filled with auxetic foam significantly outperformed all other types in terms of energy absorption and the ability to resist dynamic loads. Using auxetic foam as an internal filler It can be very effective in applications requiring high impact protection, such as military applications, automotive structures, aerospace, and shock absorbers in safety systems. Figure 14 shows that incorporating auxetic materials into engineering designs can lead to significant improvements in the mechanical performance of structural systems under severe loading conditions.

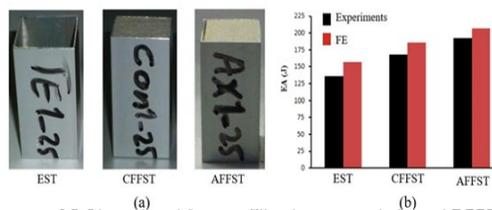


Figure 13 Standard foam-filled square tubes (CFFST), auxetic foam-filled square tubes (AFFST), and empty square tubes (EST) are among the tubes that were examined; (b) both experimental and numerical measurements were made of the tested tubes' energy absorptions (EA) [119]

To evaluate the fracture toughness of auxetic materials, several basic equations based on fracture mechanics are used, which take into account the effect of geometric shape, applied stresses, and crack propagation within the material, Stress Intensity

Factor (SIF) The stress intensity factor K is expressed in the case of tensile loading on a crack and Griffith's Energy Release Criterion According to Griffith's theory, fracture occurs when the energy released by crack growth is equal to or greater than the energy required to form a new crack surface as in the following equations:

$$\frac{2\pi K}{E} = cG \dots \dots (5) \sqrt{\pi a} \cdot \sigma \cdot Y = K \dots \dots (4)$$

For the approved standard and the shape of the standard sample.

In experimental studies of fracture toughness, standard samples are used according to ASTM or ISO specifications to evaluate the material's resistance to fracture. The most common specimens include: SENB (Single Edge Notched Bend) Specimen – ASTM E399 used to determine Mode I fracture toughness.

The specimen has a single notch on its edge and is loaded in bending. CT (Compact Tension Specimen) Specimen – ASTM E647 used in studies of crack growth under cyclic loading (Fatigue Crack Growth - FCG) has a central notch and a side notch, and is loaded in axial tension. SE(T) and SE(B) Specimen – used in studies of the elastic-plastic behavior of materials.

The geometry of the specimen directly affects the test results, so the specimen shape is chosen based on the nature of the material, the type of application, and the purpose of the study.

4.4 Fatigue Properties

According to published reports, auxetic materials' fatigue properties outperform those of traditional cellular architectures [126,127]. Bezazi *et al.* conducted empirical studies on the fatigue characteristics of ordinary thermoplastic PU foams and auxetic foams under cyclic tensile loads. As a damage index, they employed load degradation (F/F_0), which stands for stiffness degradation. Load deterioration is plotted against $r = 0.95$ and 0.725 , the number of cycles (S-N curve) at two loading levels in Figure 13 shows the relationship between the number of cycles and stiffness degradation of auxetic foams and conventional foams under different loading levels. The horizontal axis (X-Axis) represents the number of cycles, which is the number of times the cyclic load is applied to the sample, and the vertical axis (Y-Axis) represents the stiffness decrease ratio (F/F_0), which expresses the extent of the material's stiffness deterioration over time. The curves in the figure: Conventional Foam curve: shows a faster decrease in stiffness with increasing number of cycles, indicating that the material loses its load-bearing capacity over time. Auxetic Foam curve: shows a slower decrease in stiffness compared to conventional foam, indicating that auxetic foams have a higher resistance to repeated stresses. As a result, auxetic foams have a greater resistance to repeated stresses than conventional foams, making

them an ideal choice in applications that require high durability and long-term endurance, such as medical, engineering, and aerospace applications [128].

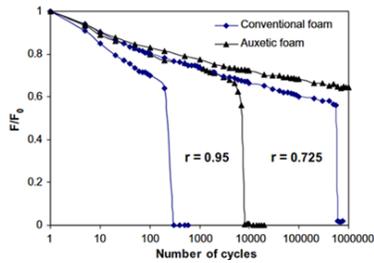


Figure 14 The graph shows how the number of cycles and stiffness degradation for auxetic and conventional foams under different loading levels relate to one another. (a) R has a value of 0.725. (b) R has a value of 0.95 [128]

4.5 Curvature Shape

The difference between auxetic materials and conventional materials is in the response to bending. When conventional materials are subjected to bending, they usually take on a saddle-shaped surface, meaning that the surface bends in two opposite directions, resulting in an anticlastic curvature. On the contrary, auxetic materials have a unique behavior where they take on a dome-shaped surface when a bending load is applied, which is known as synclastic curvature. In conventional materials, when the material is bent inward, the side faces tend to expand outward due to the positive Poisson's ratio. In auxetic materials, which have a negative Poisson's ratio (NPR), the side faces contract inward instead of expanding outward, resulting in a doubly curved surface instead of a saddle surface. This property gives the materials Oxidation has a greater ability to withstand bending loads while reducing internal stress deformation, making it ideal for applications that require high mechanical stability when subjected to bending [129, 130, 131].

Engineering applications of this phenomenon are aerospace structures and aircraft: where the dome shape helps to distribute loads more effectively and reduce concentrated stresses. Medical applications (such as prosthetics and orthotics): where this property can be used to design structures that adapt to the natural movements of the human body. Building and architectural materials: for use in curved surfaces and engineering domes that require high strength with a flexible response to external stresses [132, 133, 134]. Figure 15: Shows the difference between the mechanical response of conventional and oxidation materials under bending. Figure 15a: Shows a conventional material with a saddle bend (Anticlastic). Figure 15b: Shows an oxidation material with a double dome bend (Synclastic). Figure 16: Shows how a 3D structure composed of rotating triangles transforms from a flat shape to a fully curved structure upon application of a bending force, reflecting the unique effect of the negative Poisson

coefficient. As a result, this property makes auxetic materials an ideal choice for structures that require high bending strength without losing mechanical stability. Thanks to their unique behavior, auxetic materials could revolutionize the design of bendable structures used in engineering, mechanical, and medical applications.

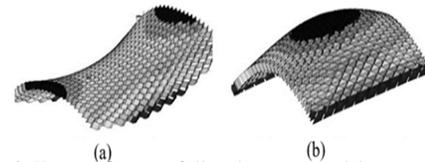


Figure 15 (a) The surface of the hexagonal honeycomb is saddle-shaped. (b) A typical example of an auxetic structure is the re-entrant honeycomb, which has a doubly curved, dome-shaped surface [129]

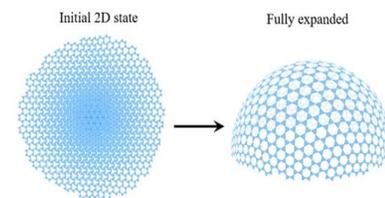


Figure 16 shows a doubly curved surface of an initial and completely extended auxetic structure composed of spinning triangles [130]

4.6 Permeability

Auxetic materials' distinct deformation behavior results in noticeably increased permeability. Alderson *et al.* [135] originally emphasized this feature by showcasing auxetics' improved filtration capabilities. As seen in Figure 17 [136], auxetic structures expand under strain in both the loading and transverse directions. Conventional cellular structures, on the other hand, only contract laterally and expand in the direction of the load. This unique property of auxetics has great promise for a wide range of uses, especially in the medical industry, such as medication delivery systems and filters.

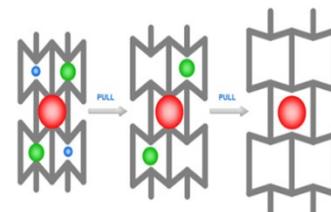


Figure 17 This illustration demonstrates how a re-entrant honeycomb may clean surfaces and get rid of contaminants. Because of its varying permeability, the honeycomb may regulate the movement of particles [135]

5.0 APPLICATIONS

Auxetic materials have proven effective in many industrial fields, making them strong candidates for use in advanced applications. This section reviews some of the most important areas that benefit from the properties of these materials.

Sandwich panels with an AXS-assembled core have exceptional qualities that enable their use in a range of unique applications, including the biomedical, textile, sports, and military sectors. Materials with complicated structures can be processed quickly thanks to AM processes, which also exhibit high precision and reproducibility. Large-scale demands find these materials appealing as a result. The primary market and uses for auxetic materials produced using AM techniques are shown in Table 2. A list of the primary uses for auxetic materials is provided in Table 1 [136, 137].

Table 1 Summary of the main applications for auxetic materials [136, 137]

Field	Applications
Aerospace	Engine vanes, vibration absorbers, wing panels, aircraft nose cones, and thermal protection
Automotive	Cushions, fasteners, sound and vibration absorbers, heat protection, and bumpers
Biomedical	Artificial skin, artificial blood vessels, bandages, ligament anchors, pressure pads for wounds, dental floss, and surgical implants
Composites	Fiber reinforcement
Military	Gloves, knee pads, bulletproof vests, helmets, and other protective equipment
Sensors/Actuators	Hydrophones, piezoelectric devices
Textiles	Fibers, useful textiles, straps or textiles that change color, and threads

Among the applications listed in Table 1, the military sector demonstrates the most promising potential for auxetic structures (AXSs). Their exceptional ability to absorb high-velocity impacts, including shock waves and bursts, makes them ideal for use in ballistic helmets and bulletproof vests [138,139]. Furthermore, auxetic materials allow for lighter and more uniform shock wave energy absorption, enhancing mobility for soldiers on the battlefield [140].

An illustrative example of their application is a shoe made from auxetic material, which reduces the impact force of body weight on the ground, thereby minimizing injuries and improving comfort [141]. This versatility underscores the broad applicability of auxetic materials in military and personal safety contexts.

6.0 RE-ENTRANT CORE SANDWICH STRUCTURES

The benefits that auxetic cores provide in sandwich structures are analyzed, including increased energy absorption and improved buckling resistance. Different designs that can be used to achieve the best mechanical performance are also discussed.

Sandwich constructions are valued for their low weight, improved bending resistance, fatigue tolerance, and energy absorption capabilities. They are therefore ideal for use in protection and aeronautical applications. [142, 143, 144, 145] These structures consist of a central core that may be arranged differently in upper and lower layers. The auxetic core, which exhibits a negative Poisson ratio upon stretching, is an illustration of a recent core shape. Researchers have paid close attention to this trait [146, 147]. Since its introduction in the 1980s, auxetic structures have attracted a lot of attention because of their many advantages [148]. The structural evolution, impact reactions, and applications of re-entrant core sandwich structures are explicitly examined in this paper. These structures fall into a variety of categories, such as gradient, hierarchical, 2D, 3D, and hybrid designs. The thorough examination of their behavior and design is emphasized in the paper.

7.0 A 2D RE-ENTRANT CELL.

This section reviews how to design two-dimensional re-entrant cells, and the effect of the tilt angle and repetition elements on their mechanical properties. The relationship between the geometric structure and energy absorption properties is analyzed, which explains why these cells are used in applications that require high flexibility and durability.

Previous studies have refined the conventional 2D re-entrant unit cell to improve various mechanical properties such as blast resistance, energy absorption, impact response, and failure mechanisms. These advancements primarily target enhancements in the design of the 2D re-entrant unit cell, as outlined in Table 2. These modifications have played a crucial role in tailoring the mechanical behavior of auxetic structures for diverse applications, further expanding their practical utility [149].

Table 2 Re-entrant core configuration design enhancements [149]

No.	Source	Design improvement	No.	Source	Design improvement
1	(Qi <i>et al.</i> , 2020), (Qi <i>et al.</i> , 2021), (Qi <i>et al.</i> , 2022)		11	(Mustahsan <i>et al.</i> , 2022)	
2	(Günaydin <i>et al.</i> , 2019)		12	(Zied <i>et al.</i> , 2015)	
3	(Hu <i>et al.</i> , 2019)		13	(Choudhry <i>et al.</i> , 2022)	
4	(Wang <i>et al.</i> , 2019)		14	(Zhu <i>et al.</i> , 2022)	
5	(Fathier <i>et al.</i> , 2021)		15	(Zhao <i>et al.</i> , 2021)	
6	(Ingrole <i>et al.</i> , 2017)		16	(Chikkanna <i>et al.</i> , 2022)	
7	(X. chun Zhang <i>et al.</i> , 2020)		17	(X. Zhang <i>et al.</i> , 2022)	
8	(Jiang <i>et al.</i> , 2020)		18	(X. Y. Zhang <i>et al.</i> , 2022)	
9	(Chen <i>et al.</i> , 2021)		19	(Liu <i>et al.</i> , 2023)	
10	(Dong <i>et al.</i> , 2023)				

8.0 POTENTIAL FOR FUTURE RESEARCH

Despite the great progress in the study of auxetic materials, there are many areas that still need to be explored. This section discusses research gaps and opportunities for future improvement.

- Use of sustainable and environmentally friendly materials: The use of natural fibers such as flax or biodegradable carbon fibers in the fabrication of auxetic can be explored, allowing for the production of more sustainable and environmentally friendly materials, while maintaining the desired mechanical properties.
- Analysis of the effect of random arrangement of auxetic: Most current studies rely on ideal geometric patterns, while practically manufactured materials may contain variations in geometric arrangement. Studying the effect of this randomness can help improve the actual performance of these materials.
- Integration with advanced manufacturing technologies: such as 3D printing and advanced modeling to create materials with enhanced performance. Nano-fabrication techniques can also be used to improve the stability of auxetic structure and increase their resistance to collapse.
- Design of hybrid and graded structures: Different materials can be combined in the same auxetic structure to achieve a better balance between stiffness and flexibility, providing improved performance in applications that require high resistance to shock and vibration.

- Studying the effect of environmental factors: such as humidity and thermal changes on auxetic structure materials, which will help improve their use in applications such as aviation and spacecraft.

9.0 SUMMARY

Auxetic materials represent a promising development in the field of mechanical engineering and smart materials, as they have unique properties that enable their use in a wide range of applications. This section discusses the practical implications of the reviewed methods as well as the main contributions of the article.

Practical implications:

- Improving the mechanical performance of materials in practical applications: auxetic materials can be used to develop shock-resistant and lightweight structures, enhancing the safety of structures in aviation and spacecraft.
- Supporting the medical industry: By applying auxetic structures in prosthetics and bone supports to improve biocompatibility and the ability of materials to withstand changing stresses.
- Developing more sustainable materials: Replacing traditional materials with natural fiber materials or hybrid composites enables the production of more efficient and environmentally friendly materials.
- Taking advantage of 3D printing technologies: It can enable the precise and complex manufacturing of these materials, opening the way for new applications such as robotics and adaptive devices.

Main contributions of the article:

- A comprehensive analysis of auxetic structures, demonstrating the impact of geometric design on mechanical performance.
- A detailed review of the latest manufacturing methods such as 3D printing and hybrid technologies.
- Identification of key research gaps that need further exploration, such as the impact of harsh environments and nonlinear loading.
- Proposing new strategies to improve performance, such as using sustainable materials and studying the effect of randomness in designs.

The study shows that auxetic materials represent an important development in the field of smart materials due to their unique properties, such as negative Poisson's ratio and high energy absorption

capacity. Future research could open up new areas for the application of these materials in various industries, especially when combined with modern manufacturing technologies such as 3D printing and nanotechnology. There are still many research opportunities to improve the stability and performance of these materials, making them a vital topic for continued exploration in the future.

Limitations of the current study

- Focus on numerical modeling: The current study relies mainly on numerical analysis and computer simulation, which may lead to differences when comparing the results with actual practical tests. Laboratory experiments are needed to validate the models used.
- Scope of materials studied: The study focuses on specific types of oxyanions, which may limit the possibility of generalizing the results to other types of materials with similar structures.
- Unstudied environmental conditions: The study did not address the effect of environmental factors such as humidity, prolonged exposure to ultraviolet radiation, or chemical corrosion, which may affect the performance of materials in real-world applications.
- Specific applications: This study focused on mechanical engineering applications only, while there may be unexplored possibilities in the fields of medicine, bioengineering, or even smart applications of oxyanions in adaptable devices. separations.

Symbol Table

PR	Poisson's ratio
NPR	Negative Poisson's ratio
AM	Additive Manufacturing
FDM	Fused Deposition Modelling
MJF	Multi Jet Fusion
SLA	Stereolithography
SLS	Selective Laser Sintering
SLM	Selective Laser Melting
EBM	Electron Beam Melting
DMD	Direct Metal Deposition
WJM	Water Jet Machining
v	Poisson's ratio
ε	Strain
ε_d	Densification strain
ε_{cd}	Onset strain of densification
ε_y	Yield strain
ε_L	Lateral strain
ε_A	Axial strain
σ	Stress
σ_y	Yield stress

σ_{pl}	Plateau stress
E	Young's modulus
E_s	Young's modulus of solid material
B	Bulk modulus
G	Shear modulus
Kh	Compliance matrix
θ^o	Re-entrant angle
L1	Inclined walls
t1	In-plane thickness
t2	Out-of-plane thickness
V_h	Volume occupied by a honeycomb

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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