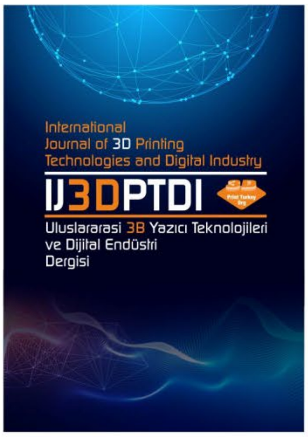

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DESIGN AND FINITE ELEMENT ASSESSMENT OF FUNCTIONALLY GRADED AUXETIC STRUCTURES

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ABSTRACT

The development of lightweight structures that utilize minimal material while maintaining desired mechanical properties has become increasingly significant with advancements in manufacturing technologies, attracting the attention of researchers. Additive manufacturing methods have enabled the rapid production and testing of new design prototypes, thereby accelerating research in this domain. This study aims to investigate new designs through the functional grading approach applied to auxetic structures. Drawing on established structural patterns from the literature, three patterns were selected for this study. These patterns were modeled with varying wall thicknesses in line with the functional grading approach, and static analyses were conducted using the Ansys Workbench program. For the static analysis, a uniform deformation value was applied to each structure, and the reaction forces at the fixed end were used as the comparison criterion. When the re-entrant, rcw-honeycomb, and elliptical patterns were redesigned using the functional grading approach, their weights increased by 13%, 9%, and 12%, respectively. However, the reaction forces, which serve as an indicator of the structures' load-carrying capacity, showed increases of 68%, 56%, and 43%, respectively. These results underscore the effectiveness of the functional grading approach in enhancing the load capacity of auxetic structures.

Keyword: Auxetic Structure, Functionally Graded Structure, Static Analysis

1. INTRODUCTION

One of the main topics of research and development (R&D) activities is developing structures that offer a lightweight design with minimal material use while meeting the desired mechanical properties. One sub-topic in this context is "auxetic" materials or structures. The term auxetic comes from the Greek word "auxetikos," meaning "that which tends to increase" [1]. Auxetic refers to materials or structures exhibiting a negative Poisson's ratio. They expand under tensile stress and contract under compressive stress. These structures typically consist of repeating units designed to deform in a specific way when subjected to external forces. This unique property makes auxetic materials useful in applications such as protective clothing, biomedical implants, and textiles.

The advantages of using auxetic materials in engineering applications are:

- Enhanced energy damping: Auxetic materials expand laterally under stress, absorbing impacts and shocks more effectively than conventional materials.
- Increased flexibility and range of motion: Useful in applications like sports equipment, auxetic materials provide increased flexibility and range of motion.
- Improved mechanical properties: Auxetic materials exhibit greater stiffness, strength, and toughness, making them useful in structural applications.
- Better fit and comfort: Conforming to the shape of the body or object they contact, auxetic materials provide a better fit and improved comfort, useful in medical devices or wearable technology.

- Improved filtration and insulation: Auxetic materials can be designed with unique pore structures that enhance filtration and insulation properties, useful in applications like air filters or thermal insulation.

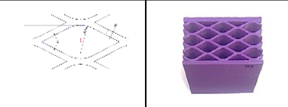
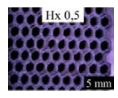
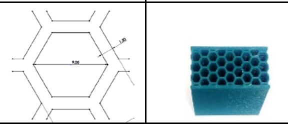
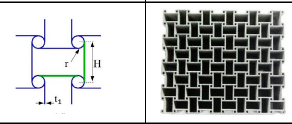
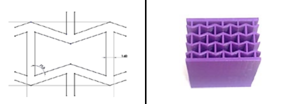
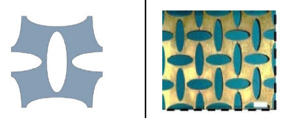
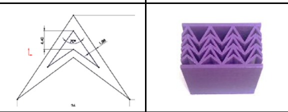
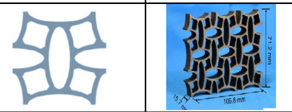
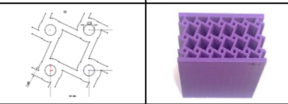
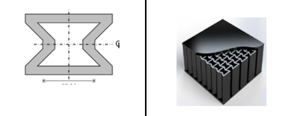
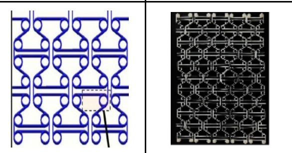
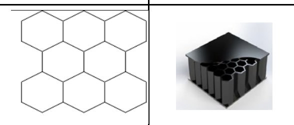
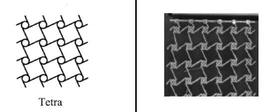
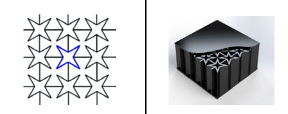
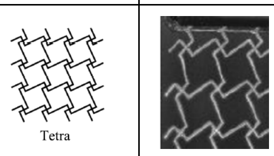
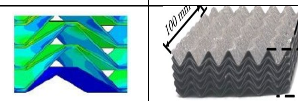
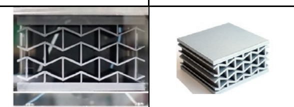
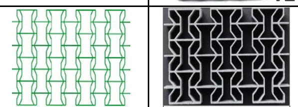
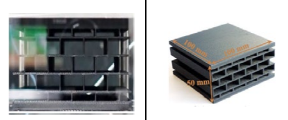
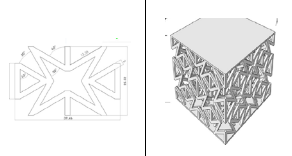
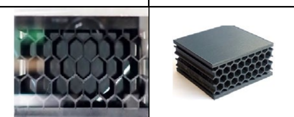
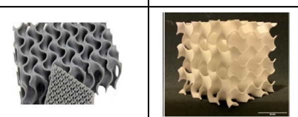
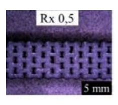
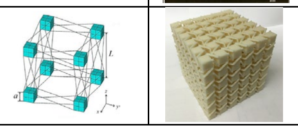
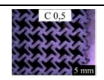
The properties of auxetic structures and their advantages largely depend on their geometry. Various geometric unit structures have been presented in the literature and continue to be developed.

Uzun [2] emphasized the need for smart materials today, pointing out that materials with new and varied properties are being developed. This study examines the new properties obtained when conventional materials have a negative Poisson's ratio and their advantageous properties during use. In B. Öztürk's [3] thesis, compression and flexure tests were performed on sandwich structures with different cell shapes. Horizontal honeycomb, vertical honeycomb, cubic, horizontal truss, vertical truss, skeleton, and gyroid geometries were used, each with fixed dimensions of 5mm×5mm×5mm. The samples, made using PLA and CFR-PLA, showed that vertical truss, vertical honeycomb, and cubic geometries had the best compressive strength and modulus of elasticity. Increased relative density slightly improved mechanical properties. A.T. Özen [4] produced "re-entrant" auxetic structures using additive manufacturing. He also created a similar "curved geometry" structure. Tensile, compression, and microhardness tests showed that adding boron nitride to PLA improved mechanical properties. Reducing the angle between branches increased the negative Poisson's ratio to -0.30. B. Ergene and B. Yalçın [5] compared traditional honeycomb structures with negative Poisson's ratio auxetic re-entrant, hybrid re-entrant, honeycomb, and chiral structures. Honeycomb structures showed a positive Poisson's ratio depending on deformation rate. Cell orientation and beam thickness affected energy absorption, with increased wall thickness improving compressive and tensile strengths. H.Y. Sarvestani et al. [6] tested three core structures using PLA and found that the re-entrant structure absorbed 33% more energy. Quasi-static uniaxial tensile tests showed that the RCA structure had higher tensile properties and auxetic effect compared to re-entrant honeycomb when loaded in the X direction. A. Alomarah et al. [7] proposed the re-entrant chiral auxetic (RCA) structure, combining hexagonal re-entrant and anti-tetrachiral honeycombs. Six samples made of photopolymer and aluminum alloy were fabricated by additive manufacturing and conventional methods. X. Liv [8] noted that improving mechanical properties of auxetic structures often compromises their negative Poisson's ratio. His study proposed two new auxetic cellular structures that maintained negative Poisson's ratios while improving Young's modulus and yield strength. C. Li [9] designed three functionally graded 3D auxetic structures, finding that they reduced dynamic deflections compared to structures with positive Poisson's ratios. Functional grading affected natural frequencies and dynamic displacement. A. Alomarah et al. [10] found that the RCA structure outperformed other honeycombs in strength and specific energy absorption when loaded in the Y direction. Only tetrachiral honeycombs outperformed the RCA in the X direction. Y. Zhou [11] focused on improving metamaterial performance through unit cell innovations. His study developed a re-entrant combined-wall (RCW) honeycomb structure, which increased Young's modulus by 120% and decreased Poisson's ratio by 43%. İ.K. Türkoğlu [12] noted that additive manufacturing advancements allow for printing auxetic structures with negative Poisson's ratios, enhancing energy absorption and durability. A. Yousefi et al. [13] investigated 3D printed auxetic structures using soft and hard polymers under various loads, showing that additive manufacturing is suitable for fabricating auxetic structures with high energy absorption and Young's modulus. Y. Zhang et al. [14] investigated the hardness of re-entrant structures, predicting that factors like entrance angles and wall thicknesses will guide future studies. O. Gülcan et al. [15] discussed functionally graded structures (FGS) and their applications in industry, noting that additive manufacturing allows for optimizing mechanical properties. A.A. Karaca [16] compared finite element analysis and experiments on stainless steel auxetic structures, showing close results and proving accuracy for auxetic structures. C. Kaboğlu [17] studied a sandwich composite with a PA 12 core and glass fiber reinforced Polypropylene for automotive bumpers, emphasizing its negative Poisson's ratio and suitability for aircraft and automotive industries. M.D. Demirbas et al.

[18] analyzed static behavior of structures with negative Poisson's ratio using ABS and PLA cores, noting their potential in high-force, low-temperature applications. F. Murat et al. [19] proposed integrating functionally graded structures into implants for better mechanical performance in biomedical applications. Y. Zhu et al. [20] developed a new tetra-incomplete chiral honeycomb structure, showing improved Poisson's ratios, elastic and shear moduli. D. Han et al. [21] investigated elliptical perforated plate-based structures, finding that specific energy absorption can be increased by reducing mass while maintaining auxetic behavior. H. Jian et al. [22] designed a lightweight structure combining elliptical perforated plates and re-entrant structures, demonstrating improved mechanical properties and utility performance. Páscoa et al. [23] Proposed a new method to investigate the effect of functionally graded structures through experimental and theoretical studies. Hu et al. focused on novel types of arc-shaped auxetic pattern by carrying out experimental and theoretical studies [24] and 3D auxetic textile structures [25].

Some common examples of auxetic structures include auxetic foams, auxetic honeycombs and auxetic lattices can be seen in Table 1. The table generally shows the preferred patterns for 2- and 3-dimensional auxetic structures and the test samples designed with these patterns. Considering the patterns in this list, the sample patterns to be discussed in this study were decided and those suitable for the functional rating approach were determined.

Table 1. 2D and 3D Auxetic Structure Patterns

Name	Patterns	Test Specimen	Ref.	Name	Patterns	Test Specimen	Ref.
Sinusoidal Slotted			[12]	Hexagonal Honeycomb	-		[5]
Hexagonal Honeycomb			[12]	Anti-tetra Chiral			[10]
Re-entrant			[12]	Oval Core Strutural-Auxetic Elliptic			[21]
Double Arrowhead			[12]	Elliptical			[21]
Tetrachiral			[12]	Re-entrant Elliptical		-	[22]
Re-entrant			[3]	Re-entrant Chiral Auxetic (RCA)			[7], [10]
Hexagonal Honeycomb			[3]	Tetra Chiral Honeybomb			[22],[10]
Star Shaped			[3]	Tetra-missing Rib Honeycomb			[22]
Triangular	-		[3]	Origami			[26]
Re-entrant			[6]	RCW Honeycomb			[11]
Rectangular			[6]	Star-Triangular Auxetic Honeycomb			[13]
Hexagonal Honeycomb			[6]	Gyroid			[13]
Re-entrant	-		[5]	Chiral 3 Dimension Truss			[27] [28]
Chiral	-		[5]				

When the studies in the literature are examined, it is seen that it is generally aimed to improve mechanical properties with new elements added to existing patterns. In this study, it is aimed to approach the subject from a different perspective. It is planned to obtain new auxetic structures by reorganizing existing structures with a functionally graded approach. A functionally graded structure (FGS) describes a material system whose mechanical, thermal or electrical properties change gradually and continuously in a controlled manner throughout the volume of the structure. In other words, a FGS is a composite material consisting of multiple layers with different material properties arranged to provide a specific performance or function. The concept of functionally graded was first introduced in the 1980s to address the limitations of traditional homogeneous materials in certain applications [29]. By varying the properties of a material in a controlled manner, FGS can offer better performance in terms of strength, stiffness, toughness and other mechanical properties and can be tailored to specific applications. FGS have a wide range of potential applications, including in the aerospace, automotive, biomedical and energy industries. For example, FGS can be used in aircraft and spacecraft components to reduce weight while maintaining strength and stiffness. In biomedical engineering, FGS can be used in implantable devices to improve biocompatibility and reduce the risk of implant failure. Overall, functional graded structures are an important area of research and development in materials science and engineering and are being studied and optimized for various applications.

Limited manufacturing possibilities, which is one of the existing disadvantages of eutectic structures, have been overcome to a great extent with the rapidly developing manufacturing technologies in recent years. The production of both auxetic and FGS with 3D printers has become very popular in recent years. With this technology, it is possible to use different materials with different properties in the same structure. In this way, the design of structures according to the desired properties of the materials has been made possible by using different 3D printer technologies such as stereolithography (SLA) or fused deposition modeling (FDM).

In the studies conducted in the literature on eutectic structures, polymer-based materials have been preferred more than metal-based materials. Polymers are engineering materials that are becoming more and more widely used in our country and in the world. The main reasons for this are ease of production, cost and obtaining lighter structures. In addition to such advantages, while high temperature and energy are required to produce metal-based materials, this need is less in polymers.

One of the disadvantages of polymers is that their operating temperature range is slightly more limited than metal-based materials. Nevertheless, it is a great advantage that polymer-based materials do not need support structures in additive manufacturing compared to metal-based materials. Within the scope of the advantages mentioned above, polymer-based materials are frequently preferred in additive manufacturing methods. Looking at additive manufacturing applications, it is seen that PLA (polyactic acid) is more widely used than other material types.

PLA is a material that is generally classified as a biodegradable thermoplastic polymer. It is derived from sugar beets, corn starch or slow-release plant materials. Therefore, it is considered an environmentally friendly material. PLA is often used in 3D printers because it has a low melting point (usually in the range of 180-220 degrees) and can thus be easily printed. It is non-toxic and offers a high print quality despite having a low tensile strength. The mechanical properties of PLA are relatively low compared to other polymer materials. For example, the tensile strength of PLA is usually 60-70 MPa [30], while the elongation at break is in the range of about 5-10%. However, it has a high hardness (usually around Shore D80), the decay or degradation time can vary depending on environmental conditions, and is available in many colors and options [31]. In conclusion, PLA was chosen for its excellent stiffness, tensile strength, and gas permeability, which are comparable to those of synthetic polymers, making it one of the most promising materials to replace petroleum-based polymers [30].

In this study, some patterns from the literature on auxetic structures were selected as examples. Previous studies have generally focused on the design of patterns with auxetic properties, their mechanical performance, testing with different materials, or using various manufacturing methods. In this study, patterns that can be easily produced with 3D printers using the FDM method were modeled with different wall thicknesses under a functional grading approach. As future manufacturing studies and experimental tests are expected to use FDM-based methods, PLA, a material suitable for this method, was selected. Although the existing process in the literature was followed regarding the method, material, and pattern, the use of the functional grading approach in the design makes this study distinct from previous ones. The selected patterns were designed in 3D and their static analyses were performed using the Ansys program. The analysis results were then used to compare the static performance of the functionally graded patterns with normal patterns, and the findings were discussed.

2. METHOD

2.1 Functionally Graded Structures

Functionally graded structures (FGS) result in property changes that gradually increase or decrease when applied to structures. Such changes can be achieved by gradual variations in material, thickness or density. Due to these characteristics, functionally graded structures offer significant advantages through their mechanical properties that vary based on their location. A functional grading method will be applied to geometries available in this study, and their wall thickness will be gradually increased.

2.2 Auxetic Structures

Auxetic structures behave unusually due to their negative Poisson's ratio. Owing to this property, when a compressive force is applied to the structure, it starts to contract instead of expanding. Likewise, when they are subjected to tension, they begin to expand instead of contract.

The mechanical properties of PLA used for parts to be used in the analyses are shown in Table 2.

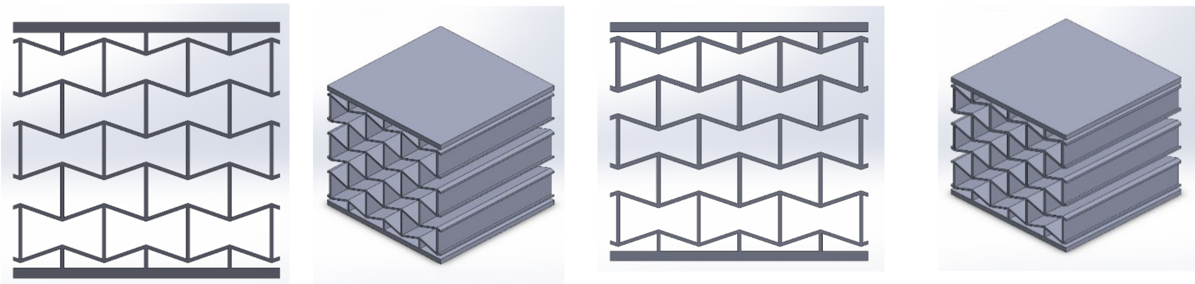
Table 2. Mechanical Properties of PLA [32]

Density (kg/m^3)	1300
Young modulus (Pa)	$2{,}34x10^9$
Poisson ratio	0,33
Bulk modulus (Pa)	$2{,}29x10^9$
Shear modulus (Pa)	$8{,}79x10^8$
Tensile yield strength (Pa)	$4{,}19x10^7$
Tensile ultimate strength (Pa)	$5{,}95x10^7$

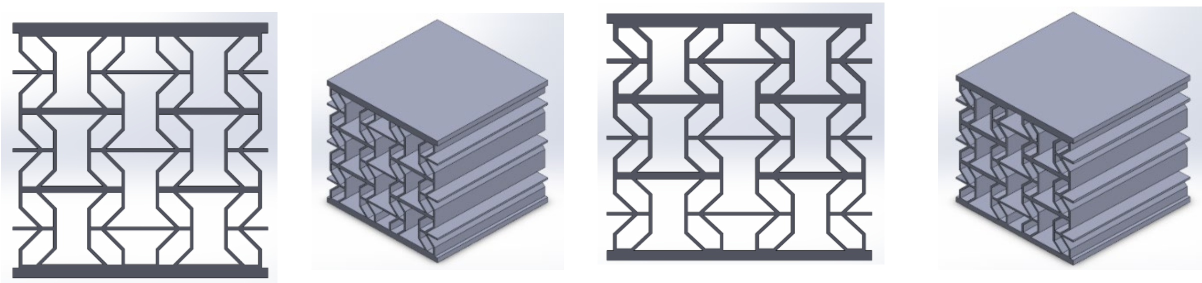
2.3 Modelling and Analysis of Auxetic Structures

The parts chosen for analysis were created using the SolidWorks computer-aided design program. Functional graded structures were designed alongside the given geometries using this program. Afterwards, the solid modelled parts were transferred to Ansys Workbench, one of the finite element method programs, for analysis. As a result, the structures will be analyzed, and the results will be evaluated. A size of 75x75x75 mm was chosen to ensure each designed geometry could achieve 3 complete core structures, facilitating comparisons. The bottom and top layers of the models were designed to be 3 mm thick, with wall thickness set at 1 mm. All functional graded parts were designed to gradually increase in thickness, from 1 mm at the bottom to 1,2 mm and 1,4 mm at the top core structures. These dimensions were selected to avoid exceeding the manufacturing constraints of fused deposition modeling (FDM) and to ensure clear geometry. The project has focused on the theoretical aspect so far. These values have been adopted to provide guidance for future experimental studies.

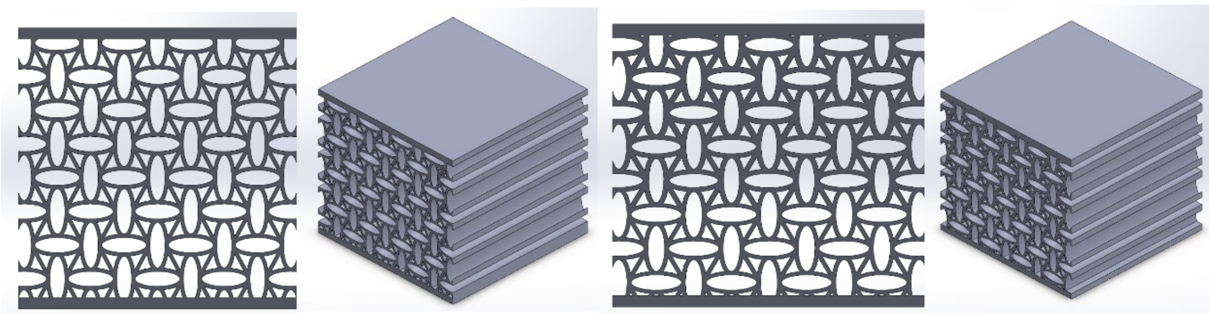
Figure 1a. displays the re-entrant structure, which is the most commonly encountered geometry of auxetic structures among the parts to be solid modelled and analyzed. The computer-aided design program Solidworks was used to create a model measuring 75x75x75x75 mm through solid modelling creation and cutting via extrusion. Figure 1b. shows the newly developed model with functional grading. The wall thickness of the model was gradually increased from 1 mm to 1,2 mm and finally to 1,4 mm from the bottom to the top. The second geometry in Figure 1c. was selected due to the RCW honeycomb structure's features, such as effective Young's modulus and high resistance to compression (increase of 120% and 140%) in comparison to classical re-entrant structures. The RCW honeycomb structure with functional grading also can be seen in Figure 1d. The third type of geometry, the elliptical structure, is given in Figure 1e. The literature review led to the selection of this structure due to its energy absorption feature [21]. Figure 1f. shows the elliptical structure with functional grading applied.



(a) Re-entrant (b) Functionally Graded Re-entrant



(c) RCW honeycomb (d) Functionally Graded RCW honeycomb



(e) Ellipse (f) Functionally Graded Ellipse

Figure 1. Selected auxetic structures

2.4 Finite Element Analysis of the Auxetic Structures

The static analysis of the structures modelled in the SolidWorks computer-aided design program was carried out in the Ansys Workbench finite element method program. Prior to conducting static analysis, the PLA material's properties listed in Table 2 were defined in the Ansys engineering data library. To perform static analysis, the SolidWorks parts saved with SLDPRT extension were transferred to the Ansys Workbench Design Modeler module. Each defined part was meshed using equal element sizing. Therefore, each experimental part was meshed with an element size of 0,8 mm. The bottom surface of each analyzed geometry was fixed and 0,5 mm displacement was defined from the top surface towards the part. Following the analysis, the structures' total deformation (mm), equivalent stress (MPA) and reaction forces (N) were obtained and evaluated. To reveal the negative Poisson's ratio of the parts more distinctly, the analysis results of the parts were scaled up by a factor of 12. This helps to better understand how the geometry will behave when compressed.

3. RESULTS AND DISCUSSIONS

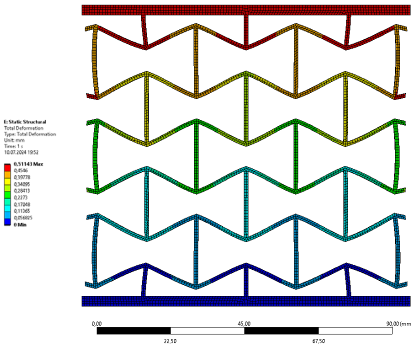
In this study, the basic mechanical behaviors of auxetic structures when they were redesigned with the functional grading approach were investigated. Using 3 basic patterns selected from the literature, they were redesigned to have different wall thicknesses, each with a functional grading approach. These models used in the finite element program were subjected to static testing to remain in the linear region under equal boundary conditions and loading conditions. To determine the load-bearing capacity of each structure, an equal amount of displacement (0.5 mm) was applied to each structure and the displacement characteristics and stress values of the structures were examined. Static analysis outputs such as the weight of each structure and displacement, stress and reaction force are shown in Table 3.

The comparison focused specifically on the relationship between reaction force and weight. Because an equal amount of displacement was applied to each structure and similar displacement results were obtained, although there were slight differences depending on the shape and displacement characteristics of the structural elements of the structures. Since static analyzes are performed in the elastic region, stress values remain far from the yield limit.

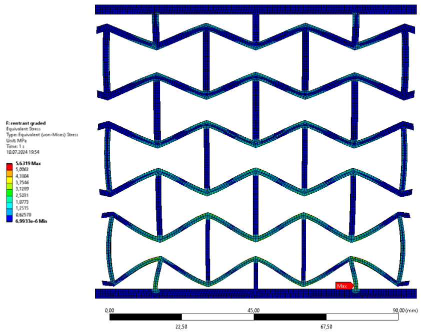
When the results are examined in this respect, functionally graded structures give better results in terms of load-bearing capacity compared to the original structures. Even if there are losses at certain rates in terms of lightweight design or increases in stresses, the fact that there are significant increases in load-bearing capabilities shows that functionally graded designs are preferable options. For example, although the FG re-entrant structure increased by 13% in weight and had a negative feature in terms of lightness, it increased by 68% in its load carrying ability. Due to this improvement in load carrying ability, the increase in weight remains insignificant. Likewise, although FG rcw honeycomb and FG ellipse structures experienced a 9% and 13% increase in weight, respectively, their load carrying capabilities increased by 55% and 43%, respectively.

Displacement characteristics are also one of the outputs that are considered important in auxetic structures and evaluated in the results. In this respect, when each building is evaluated on its own, the following can be said. While in the original designs, the elements in the buildings show a proportional change in shape from top to bottom, in the functionally graded structures, the upper parts with higher wall thickness (in the designs in this study, the wall thickness of the functionally graded structures increases from bottom to top) move with a rigid behavior and the deformation change starts from the lower parts. This feature is important in terms of providing a different displacement character to the structures. In this way, displacement becomes a controllable output. If the amount of displacement due to deformation change can be controlled through different studies, it will be possible to obtain steerable structures by ensuring that the structures change deformation in the desired direction.

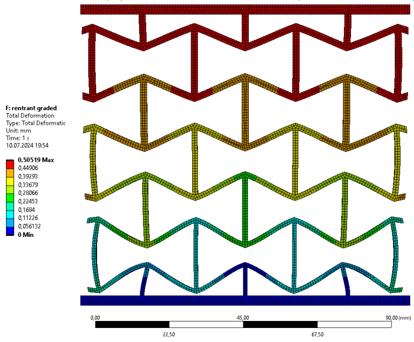
Functionally graded materials (FGMs) have spatial variations in composition and structure, resulting in tailored mechanical properties like strength, stiffness, and weight. When applied to auxetic structures, FGMs enhance overall performance. The study shows that FG auxetic structures significantly improve load-bearing capacity, crucial for high strength-to-weight ratio applications such as aerospace and biomedical implants. Additionally, FG auxetic structures exhibit unique and controllable displacement characteristics, making them ideal for applications requiring precise movement or energy absorption, like protective gear and flexible electronics.



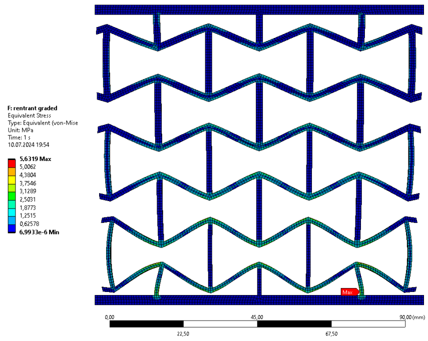
(a) Deformation (Re-entrant)



(b) Stress (Re-entrant)

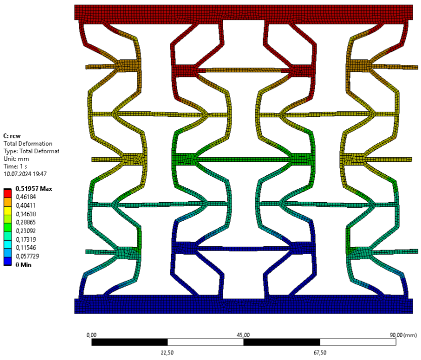


(c) Deformation (FG Re-entrant)

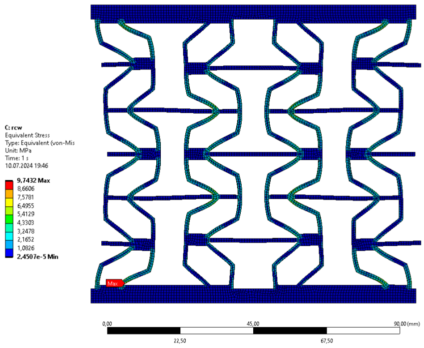


(d) Stress (FG Re-entrant)

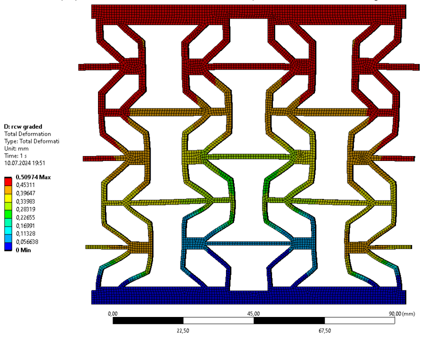
Figure 2. Deformation and stress results of re-entrant and FG re-entrant model with 0.5 mm displacement in the compression direction



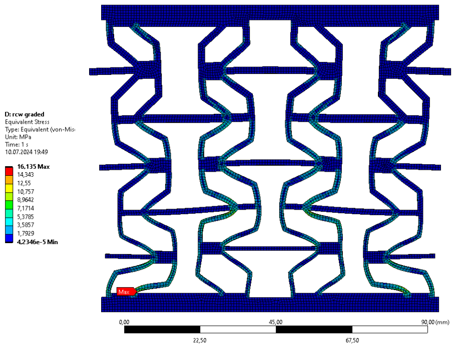
(a) Deformation (RCW honeycomb)



(b) Stress (RCW honeycomb)

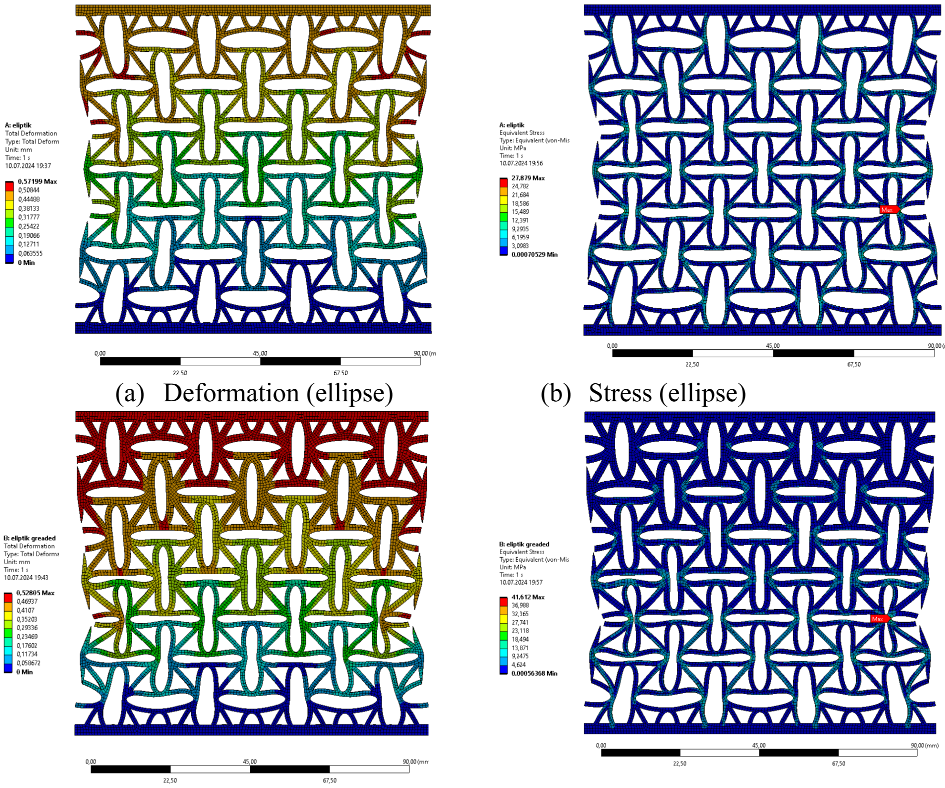


(c) Deformation (FG RCW honeycomb)



(d) Stress (FG RCW honeycomb)

Figure 3. Deformation and stress results of RCW honeycomb and FG RCW honeycomb model with 0.5 mm displacement in the compression direction



(a) Deformation (ellipse) (b) Stress (ellipse)

(c) Deformation (FG ellipse) (d) Stress (FG ellipse)

Figure 4. Deformation and stress results of ellipse and FG ellipse model with 0.5 mm displacement in the compression direction

Table 3. Analysis results of auxetic structures

	Weight (kg)	Difference (%)	Total deformation (mm)	Equivalent stress (MPa)	Difference (%)	Force reaction (N)	Difference (%)
Re-Entant Geometry	0,120	%13	0,51143	4,259	%59	57,38	%68
Functionally Graded Re-Entrant Geometry	0,136		0,50719	6,783		96,37	
RCW Honeycomb Geometry	0,151	%9	0,52034	13,827	%59	321,3	%55
Functionally Graded RCW Honeycomb Geometry	0,165		0,51068	22,061		500,2	
Ellipse Geometry	0,234	%13	0,56699	40,08	%21	2918,8	%43
Functionally Graded Ellipse Geometry	0,266		0,57888	48,828		4189,5	

4.CONCLUSION

In this study, the mechanical behaviors of auxetic structures were examined after they were redesigned using a functional grading approach. The results show that functionally graded auxetic structures have much better load-bearing capacity than the original designs, even though they have a small increase in weight. This improvement is especially clear in the FG re-entrant, FG rcw honeycomb, and FG ellipse structures, which saw large increases in their ability to carry loads—68%, 55%, and

43%, respectively—while only gaining a little extra weight. These results suggest that the small weight increase is worth it because of the big improvements in performance, making functionally graded designs a good choice for situations where strength and load-bearing capacity are important.
Additionally, the study pointed out that functionally graded auxetic structures have unique displacement characteristics. The way they deform can be controlled by changing the design. This ability to control deformation creates new possibilities for custom mechanical responses in applications that need precision and flexibility, such as in aerospace, medical implants, protective equipment, and flexible electronics.
In conclusion, using functional grading in auxetic structures not only improves their mechanical properties but also allows for new and creative design options for high-performance applications. Future research could focus on optimizing these structures for specific uses, especially by controlling how they deform to get the desired results.

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ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
CFR-PLA	Carbon Fiber Polylactic Acid
FDM	Fused Deposition Modeling
FGS	Functionally Graded Structure
PLA	Polylactic Acid
R&D	Research and Development
RCA	Re-entrant Chiral Auxetic
RCW	Re-entrant Combined-Wall
SLA	Stereolithography

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