Gazi Üniversitesi
Fen Bilimleri Dergisi
PART C: TASARIM VE TEKNOLOJİ

Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

GU J Sci, Part C, 11(4): 1081-1091 (2023)

Investigation of the Auxetic Behavior of an Original Lattice Structure Design

Nuriye Nur KAYA[1,4*], Cengiz ELDEM[2], İhsan TOKTAŞ[3]

[1] *Department of Industrial Design Engineering, Gazi University, 06560 Ankara, Turkey*
[2] *Department of Industrial Design Engineering, Gazi University, 06560 Ankara, Turkey*
[3] *Ankara Yıldırım Beyazıt University, Faculty of Architecture And Fine Arts, Industrial Design Department, Ankara, Turkey*
[4]*Department of Industrial ProductDesign, Fırat University, 23300 Ankara, Turkey*

Article Info

Research article
Received: 27/09/2023
Revision: 13/10/2023
Accepted: 14/10/2023

Keywords

Auxetic
Negative Poisson's ratio
Lattice structure
Novel auxetic structure

Makale Bilgisi

Araştırma makalesi
Başvuru: 27/09/2023
Düzeltme: 13/10/2023
Kabul: 14/10/2023

Anahtar Kelimeler

Auxetic
Negatif Poisson oranı
Kafes yapı
Yeni auxetic yapı

Graphical/Tabular Abstract (Grafik Özet)

Using finite element analysis, the Poisson's ratio of newly created auxetic lattice structures with 2x4 and 4x4 matrices and 12 various geometric internal thicknesses was examined. / Bu çalışmada, 12 farklı geometri iç kalınlığına sahip 2×4 ve 4×4 matrisli olarak yeni tasarlanmış Auxetic latis yapıların Poisson oranı sonlu elemanlar analizi kullanılarak incelenmiştir.

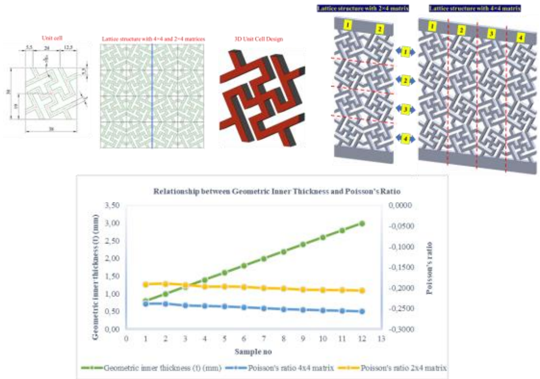

***Figure A**: The geometric internal thickness and Poisson's ratio of specified lattice systems are related. / **Şekil A:** Tasarlanan latis yapıların geometrik iç kalınlık ile Poisson oranı ilişkisi*

Highlights (Önemli noktalar)

- *A novel auxetic lattice structure geometry, not previously seen in the literature, has been created and modeled. / Literatürde bulunmayan özgün bir auxetic latis yapı geometrisi tasarlanmış ve modellenmiştir.*
- *All of the designs examined have a negative Poisson's ratio. / İncelenen tasarımların hepsi negatif Poisson oranına sahiptir.*
- *In the auxetic designs under consideration, the Poisson's ratio values got closer to -0.5 as the geometric inner thickness rose. / İncelenen auxetic tasarımlarda geometrik iç kalınlığı arttıkça, Poisson oranı değerleri -0,5'e yaklaşmıştır.*

***Aim (Amaç):** The purpose of this work is to design, examine, and establish the existence of a novel auxetic structure with a negative poisson's ratio. / Bu çalışmanın amacı, literature özgün bir Auxetic yapı tasarlayıp analizlerini gerçekleştirerek negative poisson oranına sahip olduğunu belirlemektir.*

***Originality (Özgünlük):** A novel auxetic lattice structure, not previously seen in the literature, was constructed and introduced in this study. / Bu çalışmada literatürde olmayan özgün bir auxetic latis yapı tasarlanarak literatüre kazandırılmıştır.*

***Results (Bulgular):** The greatest result in the design with sample number 12 was -0.2567 with a Poisson's ratio of 3.00 mm geometric inner thickness in a 4x4 matrix structure. / 12 numune nolu olan tasarımda 4×4 matrisli yapıda 3,00 mm geometrik iç kalınlılıkta, poisson oranı -0,2567 olarak en yüksek sonuç bulunmuştur.*

***Conclusion (Sonuç):** In this study, a unique unit cell, which is not available in the literature, was designed by using the drawing techniques of Islamic geometric patterns. According to the results of the analysis, the auxetic property of the designs increased as the geometric inner thickness increased. The analysis results of the designed lattice structures are compared with other structures in the literature. / Bu çalışmada islami geometric desenlerin çizim tekniklerini kullanarak literatürde bulunmayan özgün bir birim hücre tasarlanmıştır. Analiz sonuçlarına göre geometric iç kalınlık arttıkça tasarımların auxetilik özelliği artmıştır. Tasaralanan latis yapının analiz sonuçları literatürdeki diğer yapılarla kıyaslanmıştır.*

*Corresponding author, e-mail: nuriyenur.kaya@gazi.edu.tr
DOI: 10.29109/gujsc.1367616

GU J Sci, Part C, 11(4): 1081-1091 (2023)

Gazi Üniversitesi
Fen Bilimleri Dergisi
PART C: TASARIM VE TEKNOLOJİ

Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

http://dergipark.gov.tr/gujsc

Investigation of the Auxetic Behavior of an Original Lattice Structure Design

Nuriye Nur KAYA[1,4*], Cengiz ELDEM[2*], İhsan TOKTAŞ[3*]

[1] *Department of Industrial Design Engineering, Gazi University, 06560 Ankara, Turkey*
[2] *Department of Industrial Design Engineering, Gazi University, 06560 Ankara, Turkey*
[3]*Ankara Yıldırım Beyazıt University, Faculty of Architecture And Fine Arts, Industrial Design Department, Ankara, Turkey*
[4]*Department of Industrial Product Design, Fırat University, 23300 Ankara, Turkey*

Article Info

Research article
Received: 27/09/2023
Revision: 13/10/2023
Accepted: 14/10/2023

Keywords

Negative Poisson's Ratio
Auxetic Structure
Lattice Structures

Abstract

Auxetic structures are special structures with negative Poisson's ratio due to their geometric shapes. In these structures, transverse and longitudinal expansions are observed when tensile force is applied, while transverse and longitudinal contractions are observed when compressive force is applied. There are many different unit cell designs such as chiral, arrowhead, and re-entrant in auxetic structures. In this study, a new unique structure was designed, its structural and mechanical properties were investigated and it was aimed to contribute a new unique structure to the literature. A unique cell design is designed as a lattice structure and the behavior of the structure is investigated. All of the lattice structures were loaded at the same value, and the geometric internal thickness of the lattice structures was varied and the relationship between thickness and negative Poisson's ratio was investigated. Lattice structures designed with 12 different geometric inner thicknesses starting from 0,80 mm up to 3 mm with 0,20 mm increments and with 2×4 and 4×4 matrices were analyzed with a finite element analysis program and it was determined that all designs had negative Poisson's ratio. It was found that the structure with a 4×4 matrix and 3 mm geometric thickness exhibited the best auxetic behavior in the designed lattice structures.

Özgün Bir Latis Yapı Tasarımının Auxetic Davranışının İncelenmesi

Makale Bilgisi

Araştırma makalesi
Başvuru: 27/09/2023
Düzeltme: 13/10/2023
Kabul: 14/10/2023

Anahtar Kelimeler

Negatif Poisson oranı
Auxetic yapılar
Kafes yapı

Öz

Auxetic yapılar, içyapılarında ki geometrik şekillerinden dolayı negatif Poisson oranına sahip özel yapılardır. Bu yapılar da çekme kuvveti uygulandığında enine ve boyuna genişlemeler izlenirken, basma kuvveti uygulandığında ise enine ve boyuna daralmalar gözlenmektedir. Auxetic yapılarda kiral, ok ucu, re-entrant gibi birçok farklı birim hücre tasarımları mevcuttur. Bu çalışma ile yeni bir özgün yapı tasarlanmış, bu yapının yapısal ve mekanik özellikleri irdelenmiş ve literatüre yeni özgün bir yapı kazandırmak amaçlanmıştır. Özgün bir hücre tasarımı, latis yapı olarak tasarlanmış ve yapının davranışı incelenmiştir. Latis yapıların hepsine aynı değerde yük uygulanmış olup, latis yapıların geometrik iç kalınlıkları değiştirilerek kalınlık ile negatif Poisson oranı arasındaki ilişki incelenmiştir. 0,80 mm'den başlayarak 0,20 mm'lik artışlarla 3 mm'ye kadar 12 farklı geometrik iç kalınlıkta ve 2×4 ile 4×4 matrisli olarak tasarlanan latis yapıların analizleri sonlu elemanlar analiz programı ile gerçekleştirilmiş ve bütün tasarımların negatif Poisson oranına sahip olduğu tespit edilmiştir. Tasarlanan latis yapılarda 4×4 matrisli, 3 mm geometrik kalınlıktaki yapının en iyi auxetic'lik davranışı sergilediği bulunmuştur.

1. INTRODUCTION (GİRİŞ)

The behavior of auxetic structures is the opposite of that of conventional materials. When tensile force is given to these structures, they expand transversely, but contract transversely when compressive force is applied [1]. Due to their better energy absorption capacity [2], tensile strength [3], acoustic behavior [4], and fracture resistance [5] these structures also possess superior properties. Because of these characteristics, they have been popular in industries such as automotive, aerospace, defense, and medicine [6].

In all auxetic structures, unit cell design is crucial [7]. The improvements made to the unit cell have improved the attributes of the constructions. Numerous 2D and 3D auxetic structures have been

*Corresponding author, e-mail: nuriyenur.kaya@gazi.edu.tr
DOI: 10.29109/gujsc.1367616

created since the research of auxetic structures first began [8]. The most thoroughly researched auxetic structures have been honeycomb and re-entrant structures. Numerous improvements have been attempted to address the shortcomings of honeycomb and re-entrant structures, such as low stiffness and low strength [9,10]. The cell walls of the re-entrant structure were connected horizontally and vertically by Fu et al. [11], strengthening the structure. To increase the deformation points and crush strength of a single re-entrant unit cell, hybrid cell designs comprised of multiple cells have also been researched [9,12,13]. It has been successful in creating auxetic structures with hierarchical designs. The used cell structures' edges and walls are replaced with smaller ones in some places. Energy absorption and crush strength have greatly improved by optimizing the deformation points with these tiny substructures [14,15]. The equivalent elastic parameters of hierarchical tubes with negative Poisson's ratio under minor deformations were determined by Su et al. [16] using the Euler beam theory, and they created a new hierarchical tube with auxetic properties. Tan et al. [14] discovered that re-entrant cell structure improves the crushing force by creating cell walls with two different hierarchical patterns. Zhang et al [17], designed a new auxetic structure by combining the re-entrant cell structure with a new vertical strut investigated its mechanical behaviour, and found that the flexibility is better than the conventional re-entrant structure. Khan et al [18], similarly found that the modified form of the re-entrant structure and the negative Poisson's ratio increased compared to the conventional re-entrant structure.

Although elastic properties are usually evaluated in a linear range, plastic deformation, and cell extrusion in auxetic structures involve nonlinear behaviour [19–22]. While the majority of research is carried out statistically, the advent of additive manufacturing technologies has allowed for the efficient investigation of analytical models through experimental analysis [12,23].

In this study, a new original auxetic structure was designed and its structural and mechanical properties were studied in order to introduce a new auxetic structure to the literature. An original lattice structure was constructed inspired by a pattern in an architectural work. Starting with the geometric inner thickness of 0,8 mm and 4×4 and 2×4 matrices, designs were realized up to 3 mm by increasing +0,2 mm, and finite element analyses were performed. AlSi10Mg material was preferred as the material in the analysis. The reason for choosing this material is that auxetic structures have become important in defence, aviation, and space studies in recent years. In these sectors, weight is a very important criterion, and lightness and strength properties direct researchers to aluminium alloys. According to the results of the analysis, the negative Poisson's ratio increased as the geometric inner thickness of the lattice structure increased.

2. MATERIALS AND METHODS (MATERYAL VE METOD)

2.1. A Unit Geometry Design And Modelling
(Birim Geometri Tasarımı ve Modellenmesi)

The geometry of the unit cell was inspired by an architectural work and drawn with the grid method [24]. The aim of the design is to provide a unique auxetic structure in addition to the existing structures in the literature. Unit cell designs were realized in 2D with AutoCAD software (Figure 1). The designs drawn in 2D were converted into 3D solid models by assigning them to SOLIDWORKS drawing program. The mathematical model of the unit cell is shown in Figure 2. In the structure, K and β angle are fixed and a, b, c values are written in K. The value of x for the geometric internal thickness (t) is 0,2.

The designed unit cell was multiplied by mirroring method and 4×4 and 2×4 matrix structures were created. The unit cell was first mirrored by selecting the line in the vertical direction to mirror towards the right side. Then the mirrored parts were selected again and this time the line in the horizontal direction was selected to create a 1×1 matrix structure. In this way, necessary duplications were made with this method and matrices were obtained in desired quantities (Figure 3).

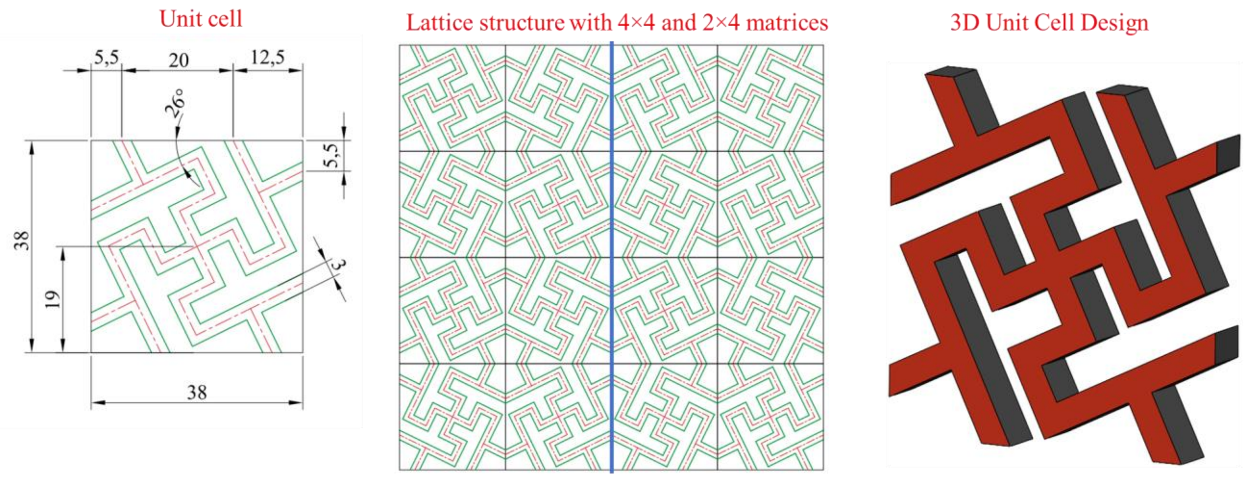

Figure 1. Formation of lattice structures using unit cells (Birim hücre ile latis yapı oluşumu)

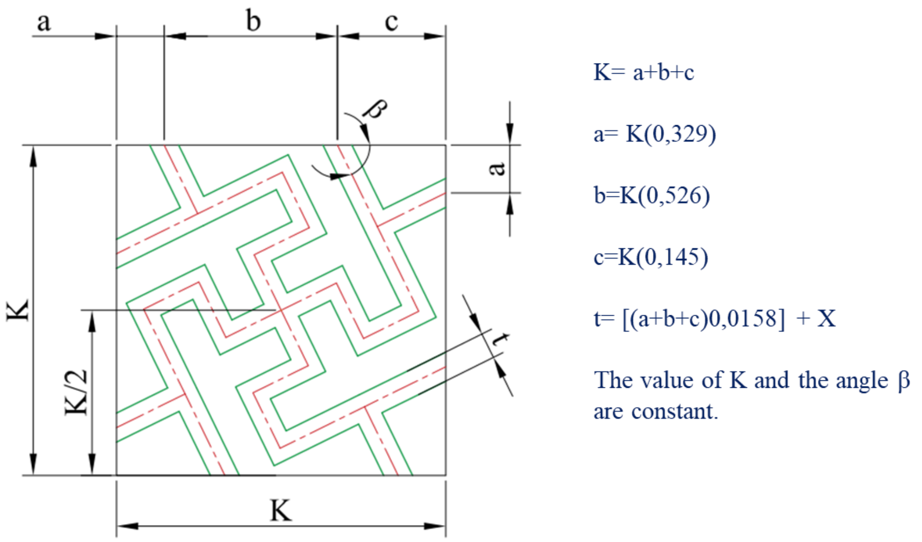

Figure 2. Mathematical model of the unit cell (Birim hücrenin matematiksel modeli)

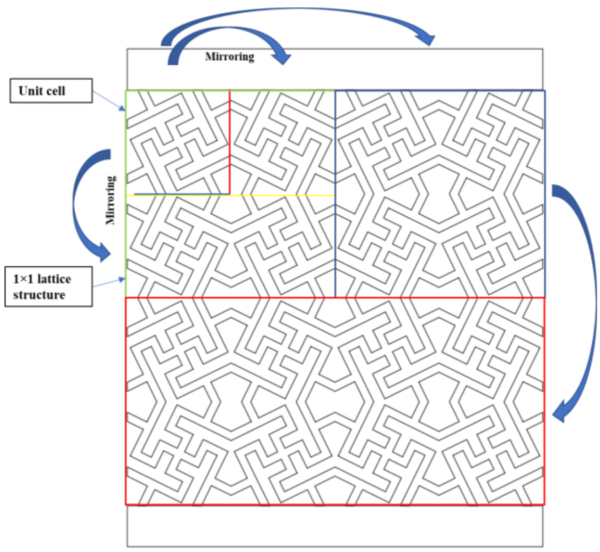

Figure 3. Modeling process of matrix structure (Matrisli yapının modellenme süreci)

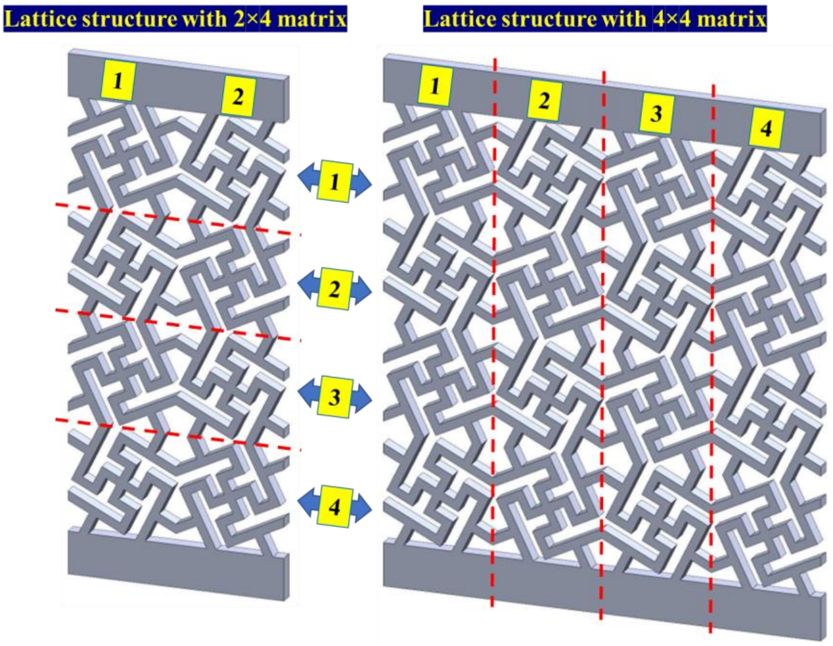

Figure 4. Lattice structures in matrix form (Latis yapıların matris şekilleri)

The purpose of replication with the mirroring method is to create successive unit cells. The fact that the matrices are different is another parameter to examine the relationship with Poisson's ratio in addition to the geometric internal thickness parameter (Figure 4).

2.2. Poisson's Ratio Calculation (Possion Oranı Hesaplaması)

Poisson's ratio is the ratio of transverse stress to axial strain and its sign is negative. However, this negativity comes from the formula and in conventional materials, there is a vertical increase in the direction of the tensile force, while a contraction occurs in the horizontal direction [25]. The positive Poisson's ratio is obtained because ε_x has a (-) sign due to the contraction here and two negative signs come together and become positive. Negative Poisson's ratio is the opposite of this situation. When an auxetic structure is subjected to a tensile force, there is an increase in the vertical direction and an expansion in the horizontal direction. In this case, the Poisson's ratio is negative with ε_x (+) sign. Poisson's ratio was calculated by using equations 1, 2, 3, 4 in the designs. Using equations 1, 2, 3, 4 in the designs.

$$\nu = -\frac{\varepsilon_x}{\varepsilon_y}, \tag{1}$$

$$\varepsilon_x = \frac{\Delta Lx}{L_{x0}} = \frac{L_{x1}-L_{x0}}{L_{x0}}, \tag{2}$$

$$L_{x1} = L_{x0}+L_{xL}+L_{xR} \tag{3}$$

$$\varepsilon_y = \frac{\Delta Ly}{L_{y0}} = \frac{L_{y1}-L_{y0}}{L_{y0}}, \tag{4}$$

Here, ν: Poison ratio, ε_x: expansion in X direction, ε_y: elongation in Y direction, ΔLx: total shape change in X direction, ΔLy: total shape change in Y direction, L_0: initial length, L_1: final length. Figure 5 details the method of obtaining L_{x1}.

2.3. Finite Element Analysis (Sonlu Elemanlar Analizi)

Finite element analysis was used to determine whether the new lattice structure has a negative Poisson's ratio. ANSYS 17.0 analysis program was used to analyze the designs saved in "x.t" format from SOLIDWORKS design program. AlSi10Mg aluminum alloy was assigned as the material in all designs (Table 1). In total, 24 different analyses were performed. A mesh with an element size of 0,75 mm was applied to the lattice structures created using the body sizing module for finite element analysis.

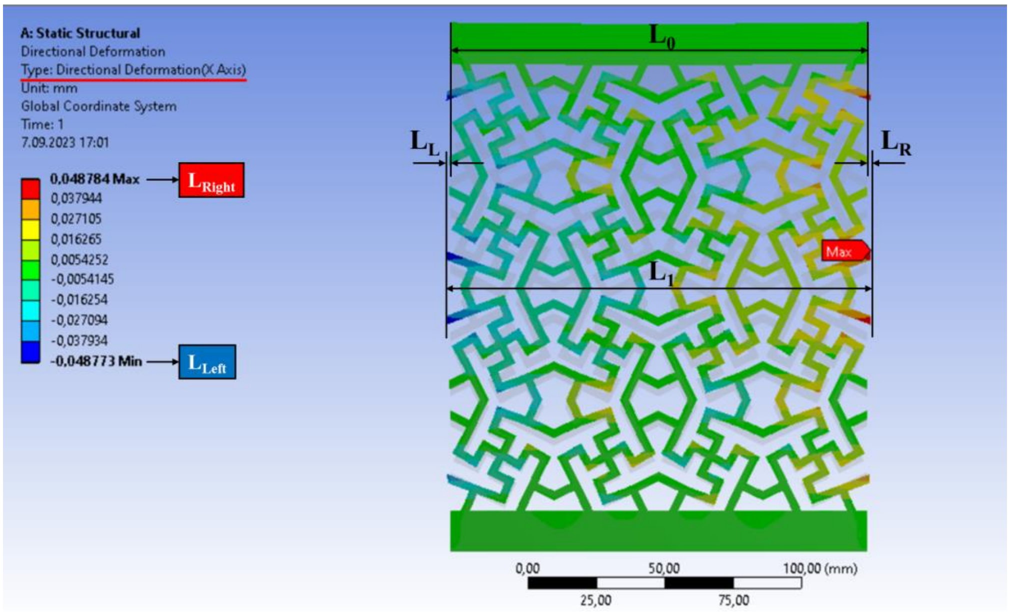

Figure 5. Schematic illustration of the ΔLx formula (ΔLx formülünün şematik gösterimi)

Table 1. Mechanical properties of AlSi10Mg aluminum alloy (AlSi10Mg alüminyum alaşımının mekanik özellikleri)

	Density (g/cm^3)	Poisson's ratio	Tensile Strength (Mpa)	Yield Strength (Mpa)	Young's Modulus (Gpa)
AlSi10Mg	**2,67 g/cm^3**	**0,33**	**440**	**240**	**70**

2.3.1. Boundary Conditions in Finite Element Analysis (Sonlu Elemanlar Analizinde Sınır Koşulları)

The boundary conditions of the design were created in order to do the analysis of the lattice structures (Figure 6). A pressure of -0,5 MPa was applied in the direction of the "*Y*" axis while the design was fastened at the bottom. Analysis was conducted without taking into account the lattice structure's weight. The shape changes in the "*X*" direction and the shape changes in the "*Y*" direction were studied to ascertain the Poisson's ratio of the designs (Figure 7). The link between the von Mises stress and total displacements with Poisson's ratio for the designed structures was also examined (Figure 8), in addition to the form changes of the designs.

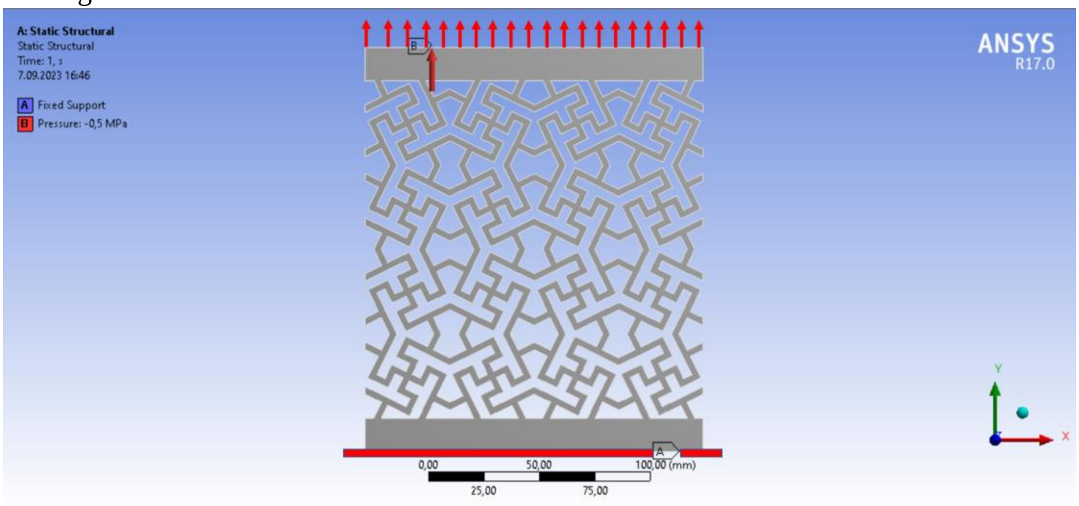

Figure 6. Boundary conditions of the lattice structure (Latis yapının sınır şartları)

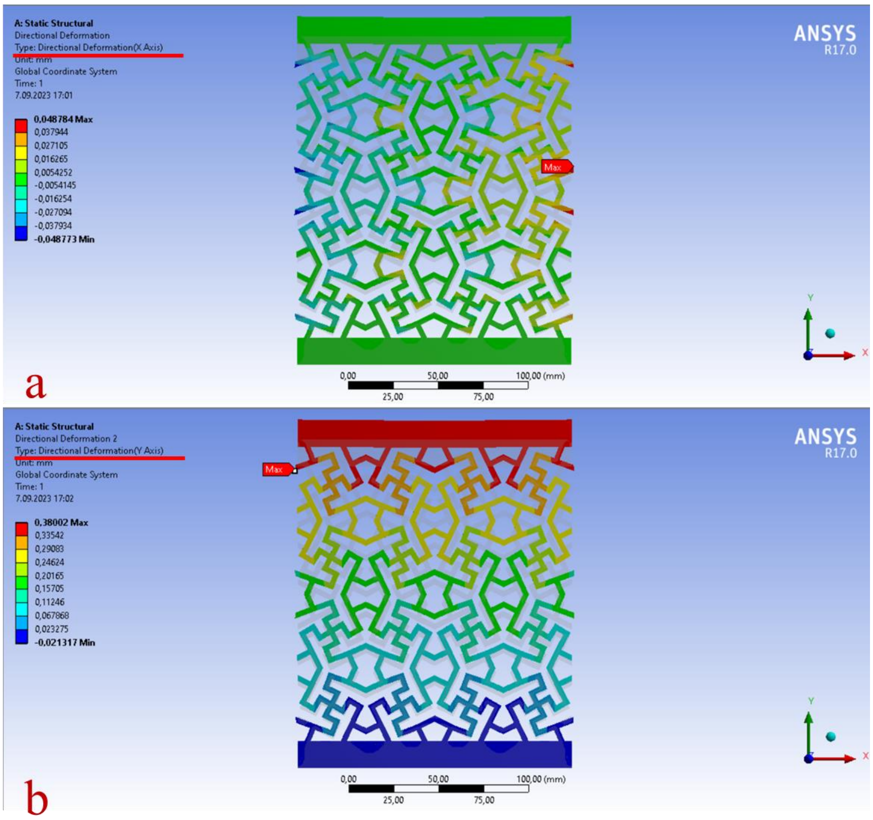

Figure 7.Shape change in X direction (a) and shape change in Y direction (b) (X yönündeki şekil değişimi (a) ve Y yönündeki şekil değişimi (b))

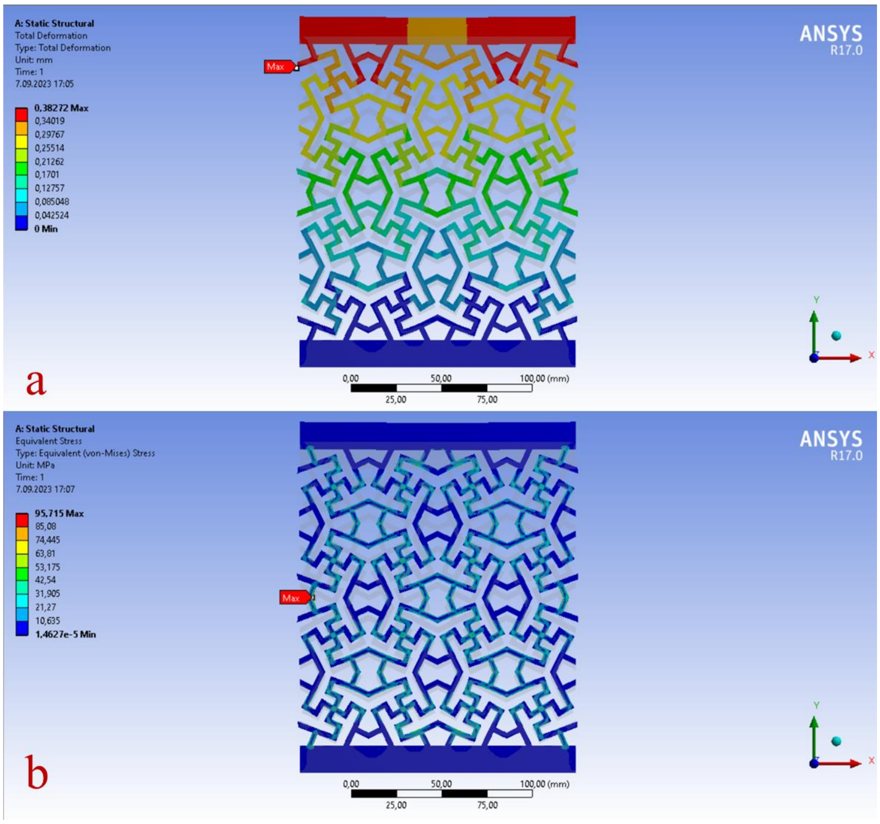

Figure 8. Total deformation (a), von Mises stress (b) ((Toplam deformasyon (a), von mises gerilimi (b))

3. RESULTS and DISCUSSION (Sonuçlar ve Tartışma)

The relationship between the geometric internal thickness and Poisson's ratio of the designed lattice structure is analyzed. A total of 24 different structures of 2×4 matrix and 4×4 matrix structures with 12 different geometric internal thickness variables were analyzed. The same value of shrinkage was applied to each of the designs. The shape changes, total deformation and von Mises stresses of the lattice structures in the x and y-axis directions were analyzed. Poisson's ratio was calculated with equations (1), (2) and (3).

$$\varepsilon_x = \frac{\Delta Lx}{L_0} = \frac{L_1 - L_0}{L_0} = \frac{0{,}0976}{152} = 0{,}00064 \qquad (2)$$

$$\varepsilon_y = \frac{\Delta Ly}{L_0} = \frac{L_1 - L_0}{L_0} = \frac{0{,}3800}{152} = 0{,}00250 \qquad (3)$$

$$\nu = -\frac{\varepsilon_x}{\varepsilon_y} = \frac{0{,}00064}{0{,}00250} \qquad (1)$$

$$\nu : \text{Poisson's ratio} = -0{,}2567$$

The Poisson's ratio of design number 12 with 3 mm geometric internal thickness was found to be -0,2567. Similar Poisson's ratio was calculated for the other lattice structures. Poisson's ratio, total deformation and von Mises stress of 4×4 and 2×4 matrix structures with geometric internal thicknesses are given in Table 2.

The relationship between the geometric internal thickness and the poison ratio for 2×4 and 4×4 matrix structures is shown in Figure 9. As can be seen from the graph with the tensile force applied to the structures, it is observed that the poison ratio of the lattice structure approaches -0,5 as the geometric inner thickness increases in the 4×4 matrix structure. As in the study by Erdoğan and Toktaş, the poison ratio increased as the thickness increased [27]. In addition, auxetic structures exhibit different behavior due to their geometry. In the study of Zhang et al [28], according to the analysis and experimental results of the re-entrant chiral structure, it was found that the Poison ratio value changed during deformation in the direction of the unidirectional applied force and showed auxetic properties in the negative direction almost up to -4.

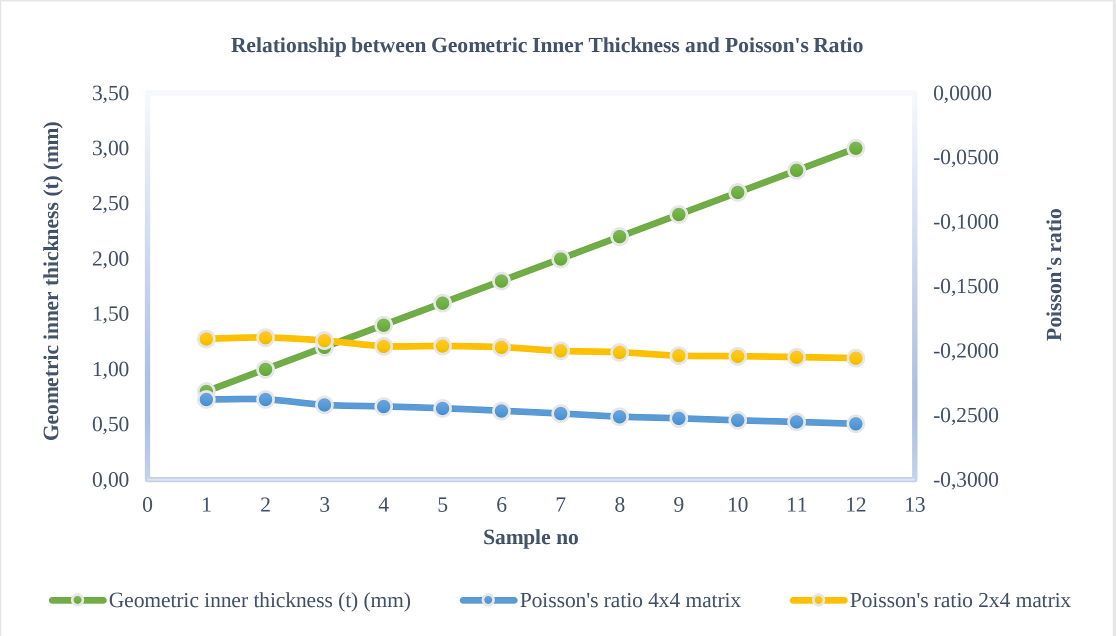

Figure 9. Relationship between geometric ınner thickness and poisson's ratio (Geometrik iç kalınlık ile Poisson oranı ilişkisi)

Table 2. Von Mises stress and total deformation results with Poisson's ratio variation (Poisson oranı değişimi ile Von Mises gerilme ve toplam deformasyon sonuçları)

Sample No	Geometric inner thickness (mm)	Poisson's ratio 4×4 matrix	Poisson's ratio 2×4 matrix	von Mises stress 4×4 matrix	von Mises stress 2×4 matrix	Total deformation 4×4 matrix	Total deformation 2×4 matrix
1	0,80	**-0,2378**	**-0,1907**	1004,4	880,34	19,6040	21,3910
2	1,00	**-0,2377**	**-0,1897**	680,85	744,34	10,1480	11,3300
3	1,20	**-0,2420**	**-0,1921**	443,51	512,37	5,8825	6,5707
4	1,40	**-0,2432**	**-0,1964**	345,09	372,26	3,6982	4,1175
5	1,60	**-0,2446**	**-0,1963**	260,47	280,52	2,4754	2,7479
6	1,80	**-0,2466**	**-0,1972**	252,37	270,98	1,7520	1,9379
7	2,00	**-0,2487**	**-0,2001**	203,77	219,34	1,2769	1,4079
8	2,20	**-0,2511**	**-0,2011**	163,32	179,65	0,9609	1,0532
9	2,40	**-0,2524**	**-0,2038**	154,88	164,02	0,7412	0,8088
10	2,60	**-0,2540**	**-0,2042**	137,95	119,14	0,5861	0,6365
11	2,80	**-0,2552**	**-0,2049**	112,19	120,07	0,4701	0,5076
12	3,00	**-0,2567**	**-0,2057**	95,715	102,35	0,3827	0,4110

The relationship between von Mises stress and Poisson's ratio is given in Figure 10. Since lattice structures can undergo plastic deformation, von Mises stress values are very important for these structures. The aim here is to ensure that the structure is not subjected to stress above its capacity and fulfills its function. In this case, the relationship between the highest von mises stress and Poisson's ratio of the lattice structure sample no 1 with a Poisson's ratio of -0,23 is given in Figure 11.

As seen in the graph, it was observed that the maximum von mises stress of the structures decreased as the Poisson's ratio increased inversely. In the study of Potheir et al. the von mises stress increased as the thickness of the unit cell increased [29]. The main reason for the two different results is due to the different geometrical structures of the unit cells. For example, it has been found that such structures have higher tensile strength and tensile strength due to the more uniform von mises stress distribution under tensile load in re-enrtant structures [30].

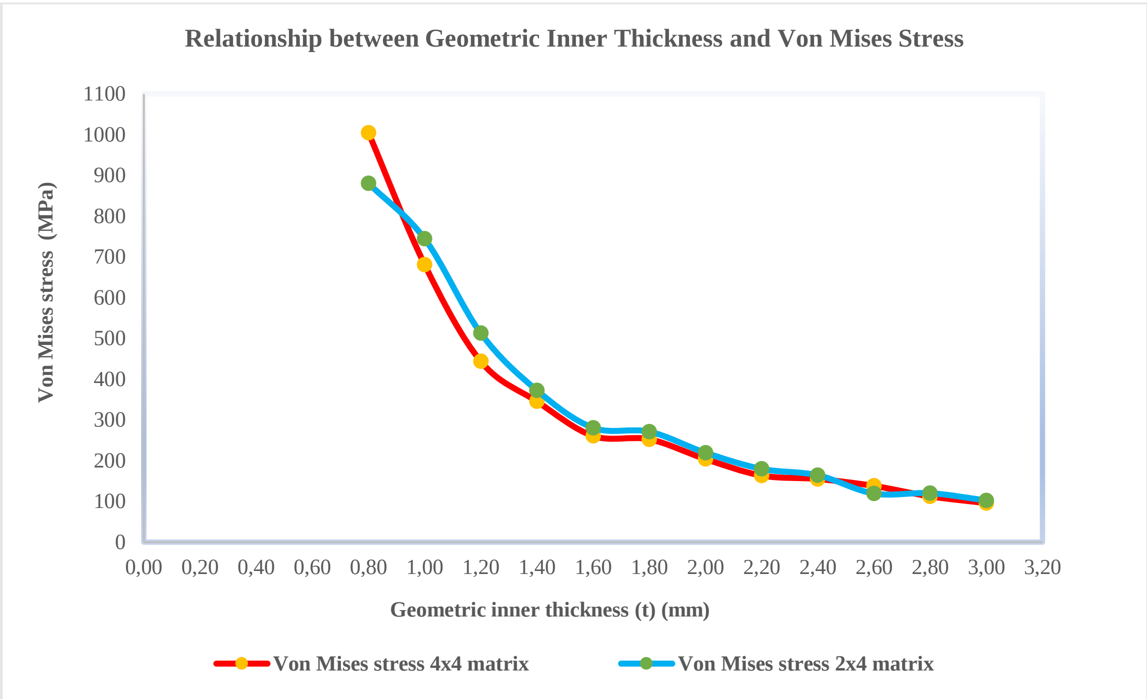

Figure 10. Relationship between geometric ınner thickness and von mises stress (Geometrik iç kalınlık ile Von mises gerilimi ilişkisi)

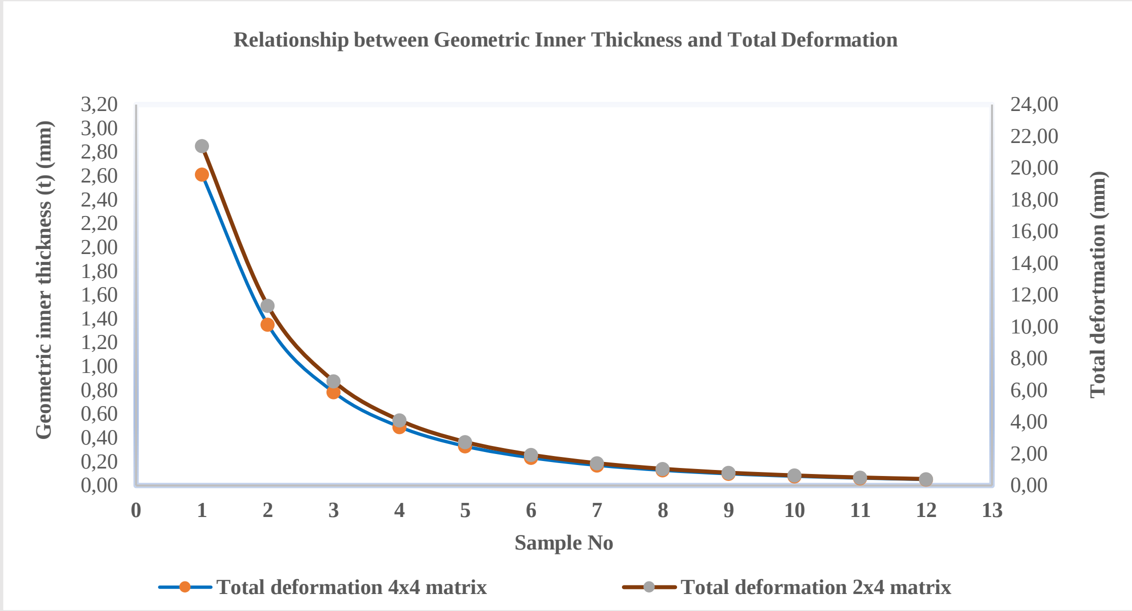

Figure 11. Relationship between geometric inner thickness and total deformation (Geometrik iç kalınlık ile toplam deformasyon ilişkisi)

It is observed that the total displacement decreases as the Poisson's ratio increases (Figure 11). As in the unit cell design by Zhang et al., high displacement was observed at low Poisson's ratio since transverse longitudinal elongations were higher at low thicknesses due to the flexibility of the structure. As the thickness of the structure increases, the total amount of displacement decreases due to the decrease in flexibility [17].

4. CONCLUSIONS (SONUÇLAR)

The Poisson's ratio of the lattice structure, which was designed inspired by the architectural pattern, was investigated by the finite element analysis method. The effects on Poisson's ratio of lattice structures by changing the number of matrices and geometric internal thickness dimensions were analyzed. In auxetic structure designs, special attention should be paid to issues such as geometric inner thickness and force direction of unit cell structures. The results found in the study are given below;

- All of the 24 lattice structures designed have negative Poisson's ratio.
- As the geometric inner thickness increased, the Poisson's ratio increased due to the geometry of the designed lattice structure.
- The lattice structure with 4×4 matrix shows more auxetic properties than the structure with 2×4 matrix
- In the 4×4 matrix structure, the highest Poisson's ratio was found in the sample with a geometric inner thickness of 3 mm
- In 2×4 and 4×4 matrix lattice structures, as the geometric inner thickness increased, the von Mises stress decreased due to the special geometric structure of the unit cell.
- In 2×4 and 4×4 matrix structures, as the geometric inner thickness increased, the total displacement decreased accordingly due to the decrease in elasticity.

ACKNOWLEDGEMENTS (TEŞEKKÜRLER)

This study was supported by Gazi University Scientific Research Projects (BAP) unit with the project numbered FDK-2022-8066.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Nuriye Nur KAYA: He has done modeling, analysis processes and article writing processes.

Cengiz ELDEM: He has contributed subject and article evaluation.

İhsan TOKTAŞ: He has contributed subject and article evaluation.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

NOMENCLATURE (KISALTMA**)**

2D	Two dimensional
3D	Three dimensional
ε	Strain
t	Geometry inner thickness
ν	Poisson's ratio

REFERENCES (KAYNAKLAR)

[1] X. Yu, J. Zhou, H. Liang, Z. Jiang, L. Wu, Mechanical metamaterials associated with stiffness, rigidity and compressibility: A brief review, Prog Mater Sci. 94 (2018) 114–173.

[2] M. Xu, Z. Xu, Z. Zhang, H. Lei, Y. Bai, D. Fang, Mechanical properties and energy absorption capability of AuxHex structure under in-plane compression: Theoretical and experimental studies, Int J Mech Sci.159 (2019) 43-57.

[3] J. Banhart, Manufacture, characterisation and application of cellular metals and metal foams, Prog Mater Sci. 46 (2001) 559–632.

[4] K.E. Evans, A. Alderson, Auxetic Materials: Functional Materials and Structures from Lateral Thinking!, Advanced Materials. 12 (2000) 617–628.

[5] C. Huang, L. Chen, Negative Poisson's Ratio in Modern Functional Materials, Advanced Materials. 28 (2016) 8079–8096.

[6] A. Alderson, K.L. Alderson, Auxetic materials, Proc Inst Mech Eng G J Aerosp Eng. 221 (2007) 565–575.

[7] R. Gatt, L. Mizzi, J.I. Azzopardi, K.M. Azzopardi, D. Attard, A. Casha, J. Briffa, J.N. Grima, Hierarchical Auxetic Mechanical Metamaterials, Sci Rep. 5 (2015) 8395.

[8] C. Qi, F. Jiang, A. Remennikov, L.-Z. Pei, J. Liu, J.-S. Wang, X.-W. Liao, S. Yang, Quasi-static crushing behavior of novel re-entrant circular auxetic honeycombs, Compos B Eng. 197 (2020) 108117.

[9] L. Yang, O. Harrysson, H. West, D. Cormier, Mechanical properties of 3D re-entrant honeycomb auxetic structures realized via additive manufacturing, Int J Solids Struct. 69–70 (2015) 475–490.

[10] C. Qi, F. Jiang, S. Yang, A. Remennikov, Multi-scale characterization of novel re-entrant circular auxetic honeycombs under quasi-static crushing, Thin-Walled Structures. 169 (2021) 108314.

[11] M.-H. Fu, Y. Chen, L.-L. Hu, Bilinear elastic characteristic of enhanced auxetic honeycombs, Compos Struct. 175 (2017) 101–110.

[12] K.P. Logakannan, V. Ramachandran, J. Rengaswamy, Z. Gao, D. Ruan, Quasi-static and dynamic compression behaviors of a novel auxetic structure, Compos Struct. 254 (2020) 112853.

[13] M. Xu, D. Liu, P. Wang, Z. Zhang, H. Jia, H. Lei, D. Fang, In-plane compression behavior of hybrid honeycomb metastructures: Theoretical and experimental studies, Aerosp Sci Technol. 106 (2020) 106081.

[14] H.L. Tan, Z.C. He, K.X. Li, E. Li, A.G. Cheng, B. Xu, In-plane crashworthiness of re-entrant hierarchical honeycombs with negative Poisson's ratio, Compos Struct. 229 (2019) 111415.

[15] Y. Chen, T. Li, Z. Jia, F. Scarpa, C.-W. Yao, L. Wang, 3D printed hierarchical honeycombs with shape integrity under large compressive deformations, Mater Des. 137(2018)226–234.

[16] Y. Sun, N. Pugno, Hierarchical Fibers with a Negative Poisson's Ratio for Tougher Composites, Materials. 6 (2013) 699–712.

[17] X. Zhang, R. Tian, Z. Zhang, G. Li, W. Feng, In-plane elasticity of a novel vertical strut combined re-entrant honeycomb structure with negative Poisson's ratio, Thin-Walled Structures. 163 (2021) 107634.

[18] S.Z. Khan, F. Mustahsan, E.R.I. Mahmoud, S.H. Masood, A novel modified re-entrant honeycomb structure to enhance the auxetic behavior: Analytical and numerical study by FEA, Mater Today Proc. 39 (2021) 1041–1045.

[19] A. Ingrole, A. Hao, R. Liang, Design and modeling of auxetic and hybrid honeycomb structures for in-plane property enhancement, Mater Des. 117 (2017) 72–83.

[20] L. Wei, X. Zhao, Q. Yu, G. Zhu, A novel star auxetic honeycomb with enhanced in-plane crushing strength, Thin-Walled Structures. 149 (2020) 106623.

[21] M. Xu, D. Liu, P. Wang, Z. Zhang, H. Jia, H. Lei, D. Fang, In-plane compression behavior of hybrid honeycomb metastructures: Theoretical and experimental studies, Aerosp Sci Technol. 106 (2020) 106081.

[22] H. Wang, Z. Lu, Z. Yang, X. Li, A novel re-entrant auxetic honeycomb with enhanced in-plane impact resistance, Compos Struct. 208 (2019) 758–770.

[23] X. Zhang, H. Hao, R. Tian, Q. Xue, H. Guan, X. Yang, Quasi-static compression and dynamic crushing behaviors of novel hybrid re-entrant auxetic metamaterials with enhanced energy-absorption, Compos Struct. 288 (2022) 115399.

[24] Jay Bonner, Islamic geometric patterns, New York, USA, 1999.

[25] M. Lei, W. Hong, Z. Zhao, C. Hamel, M. Chen, H. Lu, H.J. Qi, 3D Printing of Auxetic Metamaterials with Digitally Reprogrammable Shape, ACS Appl Mater Interfaces. 11 (2019) 22768–22776..

[26] İ. Erdoğan, İ. Toktas, Geometri İç Kalınlığının Yeni Tasarlanan Ökzetik Yapı Üzerine Etkisinin Araştırılması, Journal of Polytechnic.(2022).

[27] S. Pothier, R. Roufail, M. Malton, Unit Cell Modelling of Auxetic Structure, Journal of Minerals and Materials Characterization and Engineering. 10 (2022) 360–369.

[28] J. Zhang, G. Lu, Z. Wang, D. Ruan, A. Alomarah, Y. Durandet, Large deformation of an auxetic structure in tension: Experiments and finite element analysis, Compos Struct. 184 (2018) 92–101.

[29] S. Pothier, R. Roufail, M. Malton, Unit Cell Modelling of Auxetic Structure, Journal of Minerals and Materials Characterization and Engineering. 10 (2022) 360–369.

[30] Y. Yao, L. Wang, J. Li, S. Tian, M. Zhang, Y. Fan, A novel auxetic structure based bone screw design: Tensile mechanical characterization and pullout fixation strength evaluation, Mater Des. 188 (2020) 108424.