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): 893-902 (2023)

Investigation of an Auxetic novel lattice structure and changes in Poisson's ratio at different inner thicknesses

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Article Info

Research article
Received: 19/08/2023
Revision: 12/09/2023
Accepted: 14/09/2023

Keywords

Auxetic
Negative Poisson's ratio
Lattice structure
Novel auxetic structure

Makale Bilgisi

Araştırma makalesi
Başvuru: 19/08/2023
Düzeltme: 12/09/2023
Kabul: 14/09/2023

Anahtar Kelimeler

Auxetic
Negatif Poisson oranı
Kafes yapı
Yeni auxetic yapı

Graphical/Tabular Abstract (Grafik Özet)

In this study, the Poisson ratio of the newly designed Auxetic lattice structures with 10 different geometry inner thicknesses was examined using finite element analysis. / Bu çalışmada, yeni tasarlanan 10 farklı geometri iç kalınlığına sahip Auxetic kafes yapıların Poisson oranı sonlu elemanlar analizi kullanılarak incelenmiştir.

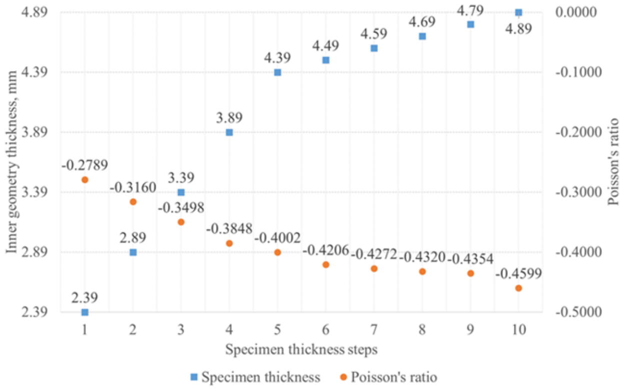

***Figure A**: Results of Poisson's ratio of examined specimens with respect to inner geometry thickness / **Şekil A:** İncelenen numunelerin iç geometri kalınlığına göre Poisson oranının sonuçları*

Highlights (Önemli noktalar)

- *A new auxetic unit geometry, which is not in the literature, has been designed and modeled. / Literatürde olmayan yeni bir auxetic birim geometri tasarlanmış ve modellenmiştir.*
- *All examined structures have negative Poisson's ratio. / İncelenen tüm yapıların negatif Poisson oranına sahiptir.*
- *When the geometry inner thickness is increased in the studied auxetic structures, the Poisson's ratio values approach -1. / İncelenen auxetic yapılarda geometri iç kalınlığı artırıldığında, Poisson oranı değerleri -1'e yaklaşmıştır.*

***Aim (Amaç):** This study aims to design and analyze new Auxetic structure for literature and application area. / Bu çalışmanın amacı, literatür ve uygulama alanı için yeni Auxetic yapı tasarlamak ve analiz etmektir.*

***Originality (Özgünlük):** In this study, a newly designed Auxetic structure that is not in the literature was examined and brought into the literature. / Bu çalışmada literatürde olmayan yeni tasarlanmış bir Oksetik yapı incelenerek literatüre kazandırılmıştır.*

***Results (Bulgular):** Poisson's ratio value was found to be -0.4599 in the auxetic structure with a geometry inner thickness of 4.89 mm determined in the 10th step. / 10. adımda belirlenen geometri iç kalınlığı 4,89 mm olan oksetik yapıda Poisson oran değeri -0,4599 olarak bulunmuştur.*

***Conclusion (Sonuç):** Within the scope of this study, unlike the auxetic structures in the literature, this unit geometry, which designed using the principles of Islamic geometric patterns and is unique in the literature, were studied. Study results showed that the auxetic structure with a highest geometry inner thickness has the lowest Poisson's ratio. The Poisson ratios of the newly designed oxetic structure were compared with the auxetic structures in the literature. / Bu çalışma kapsamında literatürdeki auxetic yapıların aksine islami geometrik desenler ilkeleri kullanılarak tasarlanan ve literatürde benzersiz olan bu birim geometri incelenmiştir. Çalışma sonuçları, geometrisi en yüksek iç kalınlığa sahip auxetic yapının en düşük Poisson oranına sahip olduğunu göstermiştir. Literatürde yer alan auxetic yapılar ile yeni tasarlanan auxetic yapının Poisson oranları karşılaştırılmıştır.*

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DOI: 10.29109/gujsc.1346281

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Abstract

Poisson's ratio, one of the most important mechanical characteristics of materials and structures, is positive for almost all of the known materials and structures. However, auxetic materials or structures have negative Poisson's ratios. Auxetic structures characteristics are very important to be used in design of a new structure. Number of computational or experimental studies on auxetic structures have been increasing in literature. In this study, a new auxetic lattice structure with different Poisson's ratios was designed and studied by finite element analysis Mechanical properties of the newly designed auxetic lattice structures were analyzed with different lattice inner thicknesses. Results showed that changes in inner thickness affect the Poisson's ratio, mass, volume and surface area of the newly designed Auxetic lattice structures.

Yeni bir Auxetic kafes yapısının ve farklı iç kalınlıklarda Poisson oranındaki değişimlerin incelenmesi

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Öz

Malzeme ve yapıların en önemli mekanik özelliklerinden biri olan Poisson oranı, bilinen malzeme ve yapıların neredeyse tamamı için pozitiftir. Ancak auxetic malzemeler veya yapılar negatif Poisson oranlarına sahiptir. Yeni bir yapının tasarımında auxetic yapıların özellikleri çok önemlidir. Literatürde auxetic yapılar üzerine hesaplamalı veya deneysel çalışmaların sayısı giderek artmaktadır. Bu çalışmada, farklı Poisson oranlarına sahip yeni bir auxetic kafes yapısı tasarlanmış ve sonlu elemanlar analizi ile incelenmiştir. Yeni tasarlanan auxetic kafes yapılarının mekanik özellikleri farklı kafes iç kalınlıklarıyla analiz edildi. Sonuçlar, iç kalınlıktaki değişikliklerin yeni tasarlanan Auxetic kafes yapılarının Poisson oranını, kütlesini, hacmini ve yüzey alanını etkilediğini gösterdi.

1. INTRODUCTION (GİRİŞ)

Poisson's ratio, one of the most mechanical characteristics of the structures, is the ratio of lateral straing to longitudinal strain at an axial tension. Poisson's ratio could be positive or negative. Structures with negative Poisson's ratios are called auxetic. Auxetic structures with newly designed lattices have been extensively studied with promising mechanical properties recently. Superior properties of auxetic structures are divided into two different groups: primary and secondary. Auxetic structures' primary properties are the negative Poisson's ratio value, synclastic behaviour, and variable permeability. Moreover, their secondary properties are improved by energy absorption, resistance to impact, shear resistance, indentation resistance, and fracture resistance.

Auxetic structures can have various lattices and unit geometries. Production of auxetic structures can be achieved by cutting machines, additive manufacturing, folding methods, and combination of these methods. Auxetic structures can be adapted to be used in many different applications such as in the aerospace and defense industries, automotive and construction industries, biomedical, sensor, and textile industries to overcome the limitations of traditional materials and structures. Auxetic structures have advantages and disadvantages according to their mechanical properties and manufacturing processes. Their advantages are high strength, lightweight, high shear modulus, high

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DOI: 10.29109/gujsc.1346281

indentation resistance, high synclastic behavior, good crack resistance, high strength-to-weight ratio, energy consumption, and changing properties by changing material or structure proportions. Moreover, their disadvantages are difficulty in manufacturing, complex structures to be used in real life applications [1].

In this study, there are studies in the literature on this subject, in which the mechanical properties of auxetic structures are examined theoretically and experimentally. [2-7]. Within the scope of this study, many kinds of production methods have been used among the studies examined, and theoretical and experimental studies in which the mechanical properties of the produced/modeled samples are tested are also included in the literature [8-14]. With the inference from the studies examined, theoretical and experimental studies in which the use of auxetic structures in the field of engineering are evaluated and tested are included in the literature [15-23].

In many studies, new manufacturing methods like additive manufacturing methods on newly designed Auxetic structure mechanical properties have been proposed. Yang et al. [24], Josewin et al. [25], Alomarah et al. [26], Gülcan and Günaydın [27], Gürkan and Sağbas [28], and Joseph et al. [29] examined the mechanical properties of newly designed and known Auxetic structures produced by additive manufacturing. Plastic deformation and strength, impact and ballistic properties, fatigue properties, tensile properties, better shock absorption performance were examined and it was observed that mechanical properties are better in newly designed auxetic structures compared to traditional lattice structures. In addition, they differ from traditional structures with their Poisson's ratio approaching -1 and dimensional improvements.

Ranjbar et al. [30], [31], and [32] made a study about the vibroacoustic performance of the Auxetic structures. They reached a conclusion that auxetic structures can affect the acoustic properties of the areas. Teng et al. [33], Zhen et al. [34], Zhang et al. [35] Yuan et al. [36], Zhang [37], Hang [38], Prasad [39] studied the energy absorption properties of auxetic structures. Zhou [40], Ruxu [41], and Mercer et al. [50] examined the newly designed 3D-printed auxetic structures' impact behavior and ballistic behavior properties.

In studies by Hana et al. [42], Kalubadanage [43], and Seetoh [44] applications of newly designed auxetic structures especially lightweight applications and properties were examined. Some structures like tubular structures, rotation structures, cubic, bioinspired structures, and composite structures were examined by using auxetic structure methodology [45-49]. New studies with auxetic about machine learning on designs of dragonfly wings, structure wings, and produced systems were examined by Ranjbar et al. [51-52].

Erdoğan and Toktaş [53] theoretically studied about effects of unit geometry of newly designed auxetic structure lattice thickness on Negative Poisson's Ratio (NPR) and mechanical properties using Finite Element Analysis (FEA). They found that the negative Poisson ratio of the newly designed unit geometry was lower than some auxetic structures found in the literature and had superior mechanical properties.

After evaluating all the previous studies, this study was carried out in order to add a new unit cell to the literature and to create a structure with superior mechanical properties from similar unit cells in the literature. In this study, the newly designed auxetic lattice structures with 10 different geometries' inner thicknesses mechanical properties were examined by using finite element analysis (FEA).

2. MATERIALS AND METHODS (MATERYAL VE METOD)

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

In this study, a unit geometry was designed newly by using Islamic geometric patterns methodology with the polygonal technique [54]. This design logic was used to create an auxetic unit cell different than the unit cells present in literature. This newly designed unit geometry is within the structural and geometric boundaries that are not present in literature. Newly designed unit geometry was used for the structure module by taking its mirror image by using SOLIDWORKS 2021 in 2D and 3D for analysis are given in Figure 1.

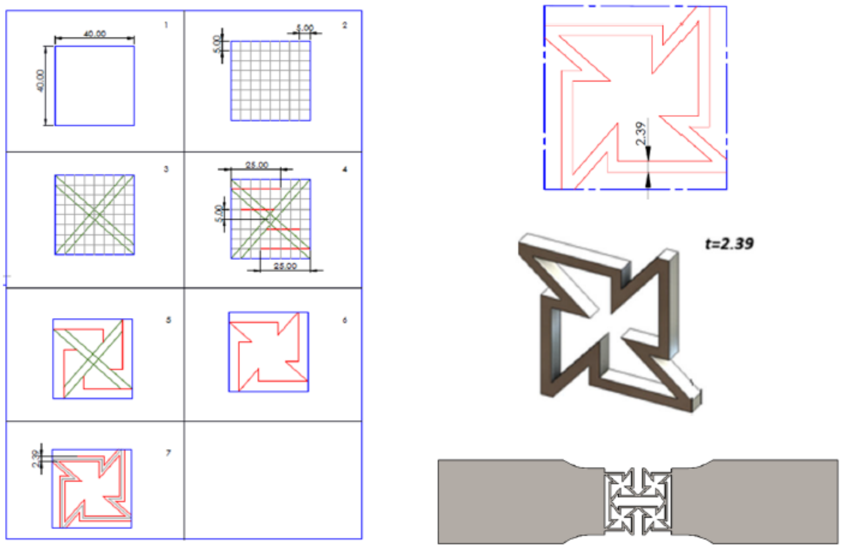


Figure 1. Design stages of the unit geometry (Birim geometrisinin tasarım aşamaları)

2.2. Analysis Structure Modelling of New Designed Auxetic Geometry (Yeni Tasarlanan Auxetic Geometrinin Analiz Yapısı Modellemesi)

In this study, newly designed unit geometry was examined in two different cases. The first case is unit geometry orientation; the second case is geometry inner thickness. ASTM, Tension Testing of Metallic Materials, Designation: E8/E8M−16a [55] was used for the production of analysis structure modeling. The analysis specimen template and dimensions are given in Figure 2.

Mechanical properties of the newly designed auxetic structure were analyzed in view of the lattices inner thicknesses. In this study, different lattices their models are given in Table 1. In order to observe the effects of structure thickness which are 2.39, 2.89, 3.39, 3.89, 4.39, 4.49, 4.59, 4.69, 4.79, and 4.89 mm on mechanical properties especially Poisson's ratio, stiffness, and stiffness/mass ratio of new designed auxetic structure were determined. There are 10 different specimens modeled by changing the geometry inner thickness in increments of 0.250 mm up to a thickness of 4.39 mm, after this thickness in increments of 0.100 mm *t* Inner lattice structure thickness was created as 4.89 mm at most. The thickness increases to be made after this thickness has not been examined since they will disrupt the structure of the geometry. On the other hand, the reason why the inner lattice structure thickness value is not less than 2.39 mm was not examined because of the newly designed unit geometry default thickness.

In the preliminary study, different values were observed when the 2×1 and 2×3 matrix structures were analyzed because they were not in the proper orientation to the geometry. Especially when the analysis in which the 2×1 matrix structure is examined, the structure exhibited anisotropic behavior. It has been observed that the 2×3 matrix structure has anisotropic properties too. In this study, 4×2, and 4×4, matrix structures were examined in terms of the application area and material structure properties, and the results were interpreted.

2.3. Analysis of Mechanical Properties (Mekanik Özelliklerin Analizi)

In this study, newly designed unit auxetic structures were investigated by using explicit dynamics analysis in ANSYS to demonstrate the effects of geometry inner thickness on the mechanical behavior of structures.

2.3.1. Poisson's Ratio (Poisson's Oranı)

The Poisson's ratio is a ratio of lateral compression strain and longitudinal extension strain on one axis stress with a negative sign. The Poisson's ratio formulation is given in Eq. 3.

$$\varepsilon_{\text{lateral}} = \frac{\Delta L}{L_O} = \frac{L_f - L_o}{L_0} \tag{1}$$

$$\varepsilon_{axial} = \frac{\Delta L}{L_O} = \frac{L_f - L_o}{L_0} \tag{2}$$

$$\nu = -\frac{\varepsilon_{\text{lateral}}}{\varepsilon_{axial}} \tag{3}$$

L_0 is the original length of the specimen, L_f is the final length of the specimen. ν is the Poisson's ratio being unitless.

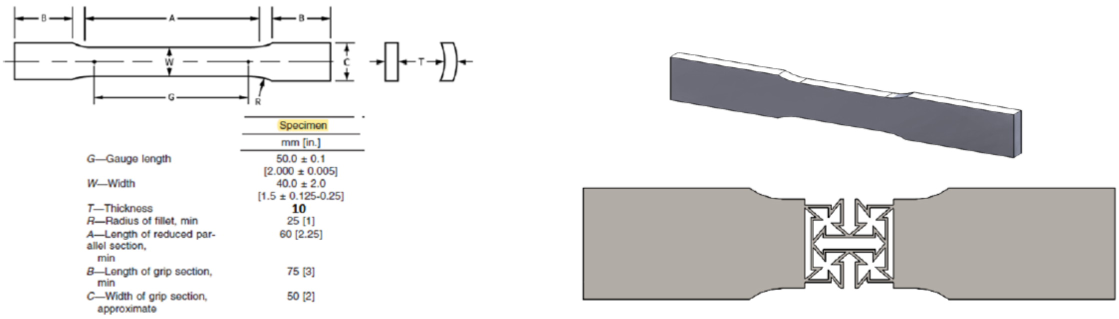
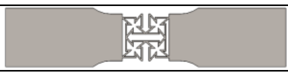
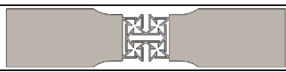
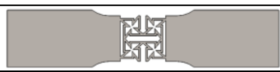
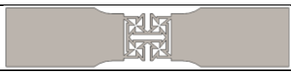
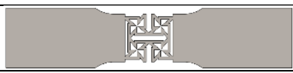
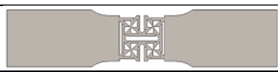
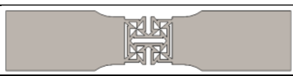
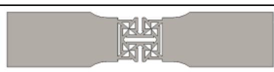
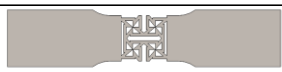
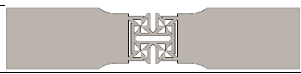


Figure 2. Analyzed specimen dimensions, template, and sample (Analiz edilen numune boyutları, şablon ve örnek)

Table 1. General properties of examined specimens (İncelenen numunelerin genel özellikleri)

Specimen No	1	2	3
Model			
Specimen thickness [mm]	2.39	2.89	3.39
Specimen mass [kg]	0.789	0.795	0.802
Specimen volume [mm^3]	100214.61	101059.73	101889.02
Specimen No	4	5	6
Model			
Specimen thickness [mm]	3.89	4.39	4.49
Specimen mass [kg]	0.808	0.815	0.815.
Specimen volume [mm^3]	102702.47	103500.10	103657.72
Specimen No	7	8	9
Model			
Specimen thickness [mm]	4.59	4.69	4.79
Specimen mass [kg]	0.817	0.818	0.819
Specimen volume [mm^3]	103814.72	103971.08	104126.8
Specimen No		10	
Model			
Specimen thickness [mm]		4.89	
Specimen mass [kg]		0.821	
Specimen volume [mm^3]		104297.37	

2.3.2. Analysis of Stiffness and Stiffness/Mass (Rijitlik ve Rijitlik/Kütle Analizi)

Stiffness/rigidity is defined as the property of maintaining its current state against a force. The stiffness value is calculated with Eq. 4:

$$S_x = \frac{F}{\delta} \tag{4}$$

F: is the force on the X-axis.
δ: is the displacement produced by the force along the same direction as a force on the X-axis.
S_x: is the stiffness on X-axis.
In addition, the stiffness/mass value is calculated using the Eq. 5:

$$S_{xm} = \frac{S_x}{m} \tag{5}$$

S_{xm}: is the stiffness/mass ratio on the X-axis.
m: mass of the structure.

In this study, stiffness, and stiffness/mass ratio were calculated using Eq. 4 and 5 in the X-axis direction since the pressure was applied along with the X force in the analysis operating setup.

2.4. Finite Element Analysis (Fea) and Boundary Conditions (Sonlu Eleman Analizi (FEA) ve Sınır Koşulları)

All models were analyzed by using ANSYS 2020 R1 for FEA. Although structural steel is frequently used in the construction sector, it is preferred in many structural parts in the automotive industry and aviation sectors due to its mechanical properties. Structural steel is used in many fields. Steel was preferred in structural analysis by taking this usage area and studies as a reference. Structural steel was selected as a material for all analyses because it negates the effect of the material parameter. Properties of the material are given in Table 3 taken from ANSYS engineering data [56].

All element size dimensions used while creating the mesh structure were determined as 2 mm for good mesh convergence. The average number of nodes is 73844 and the elements are 15500. Hex dominant method, Quad/Tri is free face mesh type was used for good meshing results. The average aspect ratio, average skewness value and Jacobian ratio are 1.103, 0.016, and 1.003, respectively. Increasing node number and element number provide good accuracy in results. Increasing the number of nodes and the number of elements increases the accuracy of the results. In this study, the error in the results was accepted as less than 1%, and mesh selection was made.

2.4.1. Static Structural Analysis Boundary Conditions and Tools (Statik Yapısal Analiz Sınır Koşulları ve Araçları)

Static structural parameters were designed to provide an analysis. Flag Red, A is denoted by pressure contact area or surface, direction, and magnitude. (Pressure is -0.2 MPa (100 N), Direction is parallel to the X-axis, Tension) and Flag Blue, B is denoted Fixed support contact area shown in Figure 3.

Poisson's ratio of lattice structures needs to be in directional deformation that is on the X-axis and Y-axis is necessary. For this reason, lateral in X-axis, and longitudinal in Y-axis directional deformations were found using the software.

3. RESULTS AND DISCUSSION (SONUÇLAR VE TARTIŞMA)

In this study, the newly designed lattice structure's mechanical performance was examined by using FEA. During FEA, examined structures were subjected to tensile test with the same load in all structures. The Poisson's ratio, stiffness, and stiffness/mass ratio values were examined.

While calculating the Poisson's ratio of the first lattice structure, the directional deformation tool in the software was used. With this tool, the deformation values of the X and Y axis were compared. The pressure acting on the analysis model in all structures and free-body diagrams, completely is the same. Calculated Poisson's ratio values were performed by examining the effects of inner lattice structure thickness.

Relations between inner lattice thickness and Poisson's ratio given in Figure 4 and Figure 5 show the effects of inner lattice thickness on lattice Poisson's ratio, mass, volume and surface area of the studied new lattice auxetic structure.

As can be seen in Figure 4, the variation of the Poisson's ratio of the examined auxetic structure with the geometry inner thickness is given. It is seen that the Poisson's ratio approaches the value of -1 with the increase of the geometry inner thickness.

The mass, volume and surface area values of the examined auxetic lattice structure are given in Figure 5. As can be seen in Figure 5, as the thickness, volume and surface area of the examined auxetic structure increase, it is seen that Poisson's ratio approaches -1.

As can be seen from Figure 5, the increase in auxetic structure mass was found to be 1% on average at each step. When evaluated in terms of the volume of the structure, it was seen that it was the largest volume at the lowest Poisson's ratio, with an increase of approximately 1% at each step. In addition, the structure surface area increased as the geometry inner thickness increased due to the unit geometry. The highest surface area was seen in the structure with the lowest Poisson's ratio. In this study, the increase in the values of the geometry inner thickness of the lattice structure, structure mass, volume and surface area brought the Poisson's ratio closer to -1. In this context, when evaluating according to usage area, mass, volume and surface area parameters must be evaluated together with Poisson's ratio.

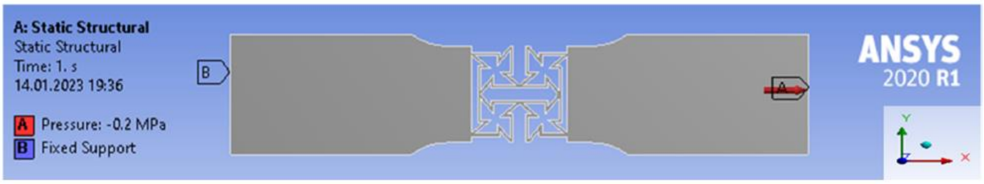


Figure 3. Boundary conditions and parameters (Sınır koşulları ve parametreler)

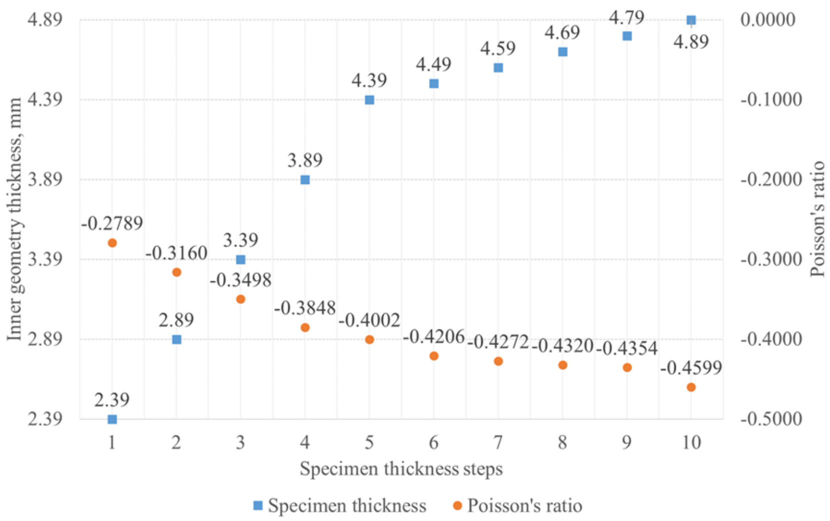


Figure 4. Results of Poisson's ratio of examined specimens with respect to inner geometry thickness (İncelenen numunelerin iç geometri kalınlığına göre Poisson oranının sonuçları)

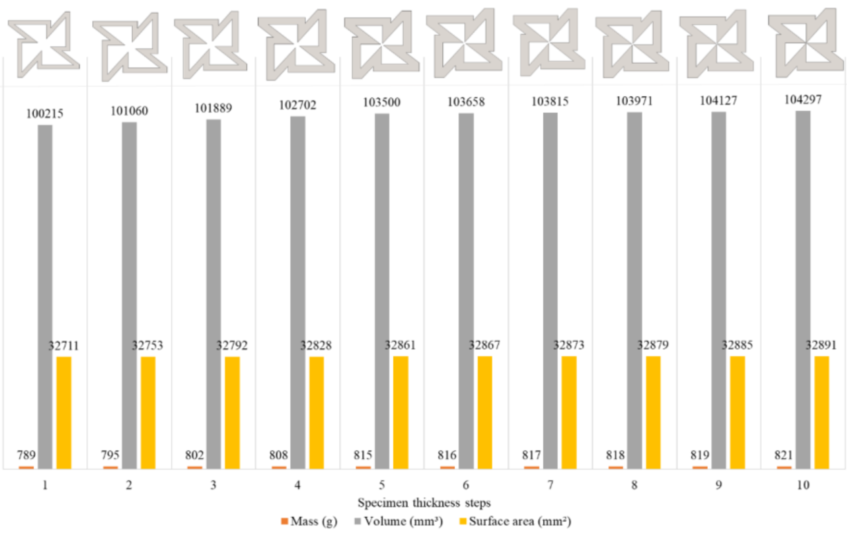


Figure 5. Examined specimens structure mass, volume and surface area (İncelenen numunelerin yapı kütlesi, hacmi ve yüzey alanı)

On the other hand, the stiffness and stiffness/mass ratio values of the analyzed structures were calculated using Eq.'s (4) and (5). In addition to Poisson's ratio analysis of examined lattice structure, the relation between inner lattice thickness and stiffness and stiffness mass ratio in this study are shown in Figure 6. When inner lattice thickness increases stiffness and stiffness/mass ratio values are increased, because that structure is more resistant to subjected forces.

For applications where mass, volume and surface area parameters are not priority, the lowest Poisson's ratio value was found to be -0.4599 in the auxetic structure with a geometry inner thickness of 4.89 mm determined in the 10th step. According to the mass, volume and surface area parameters, the selection of Poisson's ratio can be done easily from Figure 4. Stiffness and stiffness/ mass values were attached to see the effects of inner lattice thickness. Specimen 10 has high stiffness and stiffness/mass ratio than others. All examined specimens (newly designed auxetic structures) have a negative Poisson's ratio. It was observed that with the increase of the geometry inner thickness, the structure mass, volume and surface area increased and the Poisson's ratio approached to -1.

The unit geometry studied in this study is a newly designed unit geometry that is not included in the literature. The Poisson's ratio obtained in this study was compared with the Poisson's ratio of the geometries examined in the studies given in the introduction. Figure 7 shows the comparison of Poisson's ratio values obtained from some studies in the introduction section and the results of this study. The unit geometry examined in this work comes to the fore when the aforementioned parameters are analyzed, despite the fact that a healthy comparison cannot be done because weight, volume, surface area, and stiffness values cannot be obtained.

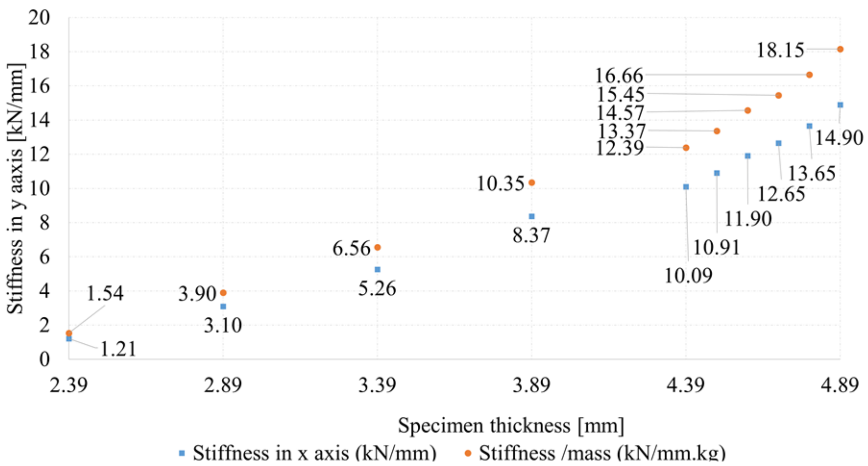


Figure 6. Results of stiffness and stiffness/mass ratio values of examined specimens with respect to inner geometry thickness (İncelenen numunelerin iç geometri kalınlığına göre sertlik ve sertlik/kütle oranı değerlerinin sonuçları)

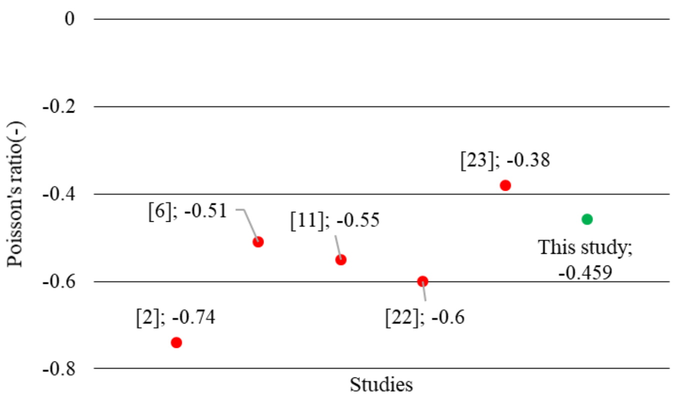


Figure 7. Comparison of the Poisson's ratio of the geometries in the literature with the Poisson's ratio obtained from this study (Literatürdeki geometrilerin Poisson oranının bu çalışmadan elde edilen Poisson oranı ile karşılaştırılması)

4. CONCLUSIONS (SONUÇLAR)

Within the scope of this study, unlike the auxetic structures in the literature, this unit geometry, which designed using the principles of Islamic geometric patterns and is unique in the literature, were studied. In this study, effects of different inner thickness changes on novel auxetic lattice structure' Poisson's ratio were performed. Study results showed that the auxetic structure with a geometry inner thickness of 4.89 mm computed in the 10th step has the lowest Poisson's ratio value of -0.4599. The newly designed and examined geometry in this study shows Negative Poisson's ratio feature as the geometries in the literature. The comparison of the Poisson's ratios of the newly designed auxetic structure with the auxetic structures in literature examined. Lattice structures are lighter than other full structures. They are suitable for lightweight applications.

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.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

İsmail ERDOĞAN: He has done modeling, analysis processes and article writing processes.

Modellemeyi yapmış, sonuçlarını analiz etmiş ve maklenin yazım işlemini gerçekleştirmiştir.

İhsan TOKTAŞ: He has contributed subject and article evaluation.

Konu ve makale değerlendirmesine katkıda bulunmuştur.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

NOMENCLATURE (KISALTMA)

2D	Two dimensional
3D	Three dimensional
ABS	Akrilonitril bütadien stiren
δ	Displacement
ε	Strain
f	Final status
F	Force in X-axis
FEA	Finite element analysis
FEM	Finite element method
L	Length
L_f	Final length
L_o	Original length
m	Mass of the structure
NPR	Negative Poisson's ratio
o	Original status
PLA	Polylactic acid
S_x	Stiffness on X-axis.
S_{xm}	Stiffness/mass ratio on the X-axis.
xm	X axis stiffness/mass
t	Geometry inner thickness
x	X axis
ν	Poisson's ratio

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