

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**STRUCTURAL DESIGN AND ANALYSIS OF AN IMPACT RESISTANT
AUXETIC METAMATERIAL**



M.Sc. THESIS

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Department of Defence Technologies

Defence Technologies Programme

FEBRUARY 2021

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**DARBE DAYANIM ÖZELLİKLİ AUXETIC METAMALZEMENİN
YAPISAL TASARIMI VE ANALİZİ**

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Date of Submission : 20 January 2021
Date of Defense : 19 February 2021





To my family,



FOREWORD

Firstly, I would like to express my sincere gratitude to my respectful advisor Assoc. Prof. Dr. Mesut Kırca, for his continuous support, guidance, and availability during thesis project and throughout my study at Istanbul Technical University.

Secondly, I would like to thank to my friends and colleagues, Emre Çalık and Ömer Çelebi for their support by sharing their mechanical design point of view.

Furthermore, I want to thank to my friend M. Tarık Köşeler, Ş. Kaan Can, Ş. Cemre Yaman, and Erdi Peker who spend their special time to increase my motivation during the completion of this thesis study.

Last but not least, I would like to express my infinite thanks to my mother D. Nezahat Gök, my father Salih Gök, and my sister Çiğdem Gök Karabulut for their endless beliefs on me, and supports in every steps in my life.

January 2021

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ABBREVIATIONS

AM	: Additive Manufacturing
BC	: Boundary Condition
CAD	: Computer Aided Design
CAM	: Computer Aided Manufacturing
CDC	: Centers for Disease and Control Prevention
EBM	: Electron Beam Melting
FBD	: Free Body Diagram
FDM	: Fused Deposition Modelling
FEM	: Finite Element Method
HIP	: High Impact Polystyrene
LBM	: Laser Beam Melting
NPR	: Negative Poisson's Ratio
PEEK	: Poly Ether Kethone
TBI	: Traumatic Brain Injury



SYMBOLS

E	: Elasticity Modulus
V	: Volume
σ	: Normal Stress
τ	: Shear Stress
d	: Diameter
ε	: Unit Strain
A	: Cross Section Area
F	: Force
δ	: Strain Deformation
t	: Thickness
ν	: Poisson's Ratio
ρ	: Density
γ	: Shear Angle
G	: Shear Modulus
P	: Pressure
K	: Bulk Modulus
K_{Ic}	: Fracture Toughness
I	: Inertia Moment
D	: Bending Stiffness



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STRUCTURAL DESIGN AND ANALYSIS OF AN IMPACT RESISTANT AUXETIC METAMATERIAL

SUMMARY

From past to present, it has been aimed to achieve to have superior performance in materials by developing the properties such as strength, impact resistance, lightness and adaptability to the texture. Generally, it has been succeeded by creating novel designs with the existing materials and/or the developments in the material science. As a result, low density and high stiffness designs such as porous structures and sandwich structures have been studied in aviation, automotive, sports competitions and military applications. Its superior performance especially in the field of shock absorption has made auxetic materials indispensable for engineers and designers. Auxetic materials are rare materials that show negative Poisson's ratio (NPR). Contrary to the materials known in the literature, thickening in the lateral cross-section when pulling is applied; they are the materials that react to contraction in lateral cross-section when applied to compression.

In this thesis, it is aimed to create a novel design that is different from the previous design studies of auxetic materials in the literature. Since the NPR property is derived from the change of geometry, not the material, an example was created for original designs in the future. Various structures in nature were examined before the novel design was created. Apart from that, it was also inspired by the shapes in the architectural works of various civilizations. Computer aided design (CAD) software was used during the design activities.

After the novel design was determined, various materials in the literature were searched. In particular, it is aimed to select materials that can be easily produced in terms of additive manufacturing (AM) today. Production method types are also mentioned. It was emphasized that the parameters of various production methods in additive manufacturing will change the mechanical property behaviour on the final structure. In future studies, it was emphasized that the test result should be investigated with numerical analysis of the novel design. It was also stated that different mechanical properties that will arise as a result of the differences in production methods should be investigated.

The unit cell of the novel design was designed with specific parameters. The effect of changing these parameters is also stated. The unit cell has been reproduced in various directions, especially in order to benefit in impact applications. While doing these design steps, the NPR property is preserved.

After the novel design creation phase, the mechanical properties of the structure were analyzed using the finite element method (FEM). In this context, displacements in tension and compression directions were applied. As a result of these, the direction and amount of deformation in the cross sections are specified. In addition, the impact energy absorption capacity of the structure was also examined. The specific damping energy of the novel structure was revealed as a result of the impact results obtained at various speeds.

These results are important in providing a new fundamental understanding of new auxetic structure property relationships and hybrid honeycomb structures for potential aerospace and defense technology products. Novel designs are expected to become

more common in the future. Multiple revolutionary inventions have been witnessed in the history of engineering with inspiration from nature and living structures. Imitating nature is not a plagiarism in terms of creating original designs; on the contrary, it means opening the door to new inventions. Within the scope of this thesis, it is aimed to reduce the weight of the structure and to prevent loss of strength by using mathematical optimization methods of the novel auxetic meta-material that has been added to the literature. It is anticipated that a complex hierarchical structure will occur in the structure as a result of optimization. It is aimed to realize the numerical calculations made as a result of the manufacturing of the hierarchical structure to be formed by additive manufacturing methods and measuring the strength in test rigs.



DARBE DAYANIM ÖZELLİKLİ AUXETIC METAMALZEMENİN YAPISAL TASARIMI VE ANALİZİ

ÖZET

Geçmişten günümüze, yüksek mukavemet, darbe sönümleme özelliği, hafiflik ve dokuya uyum gibi üstün özelliklere sahip malzeme geliştirerek ya da mevcut malzemeye özgün tasarımlar yaratarak hedeflenen performansı elde etmek amaçlanmıştır. Bu neticede, gözenekli yapılar, sandviç yapılar gibi beraberinde getirdiği düşük yoğunluk yüksek mukavemet özellikli tasarımlar üzerinde havacılık, otomotiv, spor müsabakaları ve askeri uygulamalarda çalışılmıştır.

Mühendislikte bilgisayar kullanımının artması, malzeme teknolojisinin gelişmesi ve yeni üretim yöntemlerinin ulaşılabilir olması tüm endüstrilerde daha yüksek başarı oranlarının elde edilmesini sağlamıştır. Özellikle savunma sanayiinde milletlerin daha üstün özellikli ürünleri ortaya çıkartma yarışında mühendislik büyük rol oynamıştır. Ayrıca spor müsabakalarında daha yüksek performansların elde edilmesi için yüksek başarılı hesaplamalı bilim dallarından faydalanılarak daha önce elde edilmemiş başarılar mümkün kılınmıştır.

Son 30 yıl içerisinde, malzeme teknolojisinin geliştirilmesinin yanı sıra tasarım özelinde yapılan çalışmalarda da mühendislik veriminin ve performansının daha hafif yapılarda elde edilmesi sağlanmıştır. Bu tezin de konusu olan darbe dayanımı için geliştirilen yeni tasarımlar üzerindeki araştırmalar her geçen gün daha da artmaktadır. Günümüzde akıllı malzemelerin geliştirilmesi temel olarak hem mikro hem de makro ölçeklerde malzeme tasarımının değiştirilmesi ile gerçekleştirilmektedir. Örnek olarak uzay çalışmalarında aynı son ürün ile birden çok fonksiyonelliğe sahip mekanizmalar üzerinde çalışılmaktadır. Metamalzemeler bu alanda araştırmaların odağındadır. Özellikle darbe sönümleme alanında gösterdiği üstün performans auxetic malzemeleri mühendis ve tasarımcılar için son yıllarda vazgeçilmez kılmıştır. Auxetic malzemeler negatif Poisson's oranı (NPR) özelliği gösteren ender malzemelerdendir. Literatürde bilinen malzemelerin aksine çekme uygulandığında yanıl kesitte kalınlaşma; basma uygulandığında yanıl kesitte daralma tepkisi veren malzemelerdir. Bu sayede darbe uygulama yönünde normal şartlarda etki yönünden uzaklaşmaya çalışan malzemeler Auxetic tasarım ile etki doğrultusuna doğru bir yoğunlaşmak gösterir. Bu davranış yapının darbe sönümleme enerjisi etkinliğini artırır.

Bu tezde auxetic malzemelerin literatürde yapılmış olan tasarım çalışmalarından farklı olan özgün bir tasarım yaratmak amaçlanmıştır. Özgün tasarım oluşturulmadan önce literatürdeki çalışmalarda en çok kullanılan yeniden girişli(re-entrant) ve kiral (chiral) yapıdaki metamalzemelerden ilham alınmıştır. Kiral auxetic metamalzeme, ayna görüntüsünde üst üste konulamayan bir geometriye sahip olan auxetic malzemenin bir alt ailesidir. Yeniden girişli petekler veya periyodik gözenekli malzemeler gibi simetrik yardımcı malzemelerle karşılaştırıldığında, kiral malzemeler deterministik kullanıma sahiptir ve bu nedenle, hem küçük hem de büyük deformasyonlarla üretim hataları altında daha sağlam yardımcı etkilere sahip olmaları beklenir. Yenilikçi tasarımlar aracılığıyla, mevcut kiral auxetic metamalzemelerin veri tabanı önemli ölçüde genişletilmiştir; yeni mekanik özelliklerin ve davranışların keşfini hızlandırılmıştır. Ayrıca, genişletilmiş veri tabanı, klasik süreklilik teorisi içinde veya ötesinde gelişmiş yapısal modellerin geliştirilmesini sağlar. Bu sebeple özgün tasarım salt yeniden girişli auxetic malzeme oluşturmak yerine kiral yapının da etkisi dahil

edilmiştir. NPR özelliği malzemesel değil geometri değişiminden ortaya çıktığı için gelecekteki özgün tasarımlar için de bir örnek oluşturulmak istenmiştir.

Özgün tasarım oluşturulmadan önce doğadaki çeşitli yapılar incelenmiştir. Bunun dışında çeşitli uygarlıkların mimari eserlerindeki şekillerden esinlenilmiştir. Tasarım faaliyetleri süresince Siemens NX12 bilgisayar destekli tasarım yazılımı kullanılmıştır. İlk özgün tasarım oluşturulduktan sonra geometri değişiminin yapının mekanik davranışlarında nasıl bir etkiye sahip olduğunun gözlenmesi için değişik üç parametre ile tasarım çeşitlendirilmiştir. Mekanik davranışlar karşılaştırmalı olarak sunularak hangi parametrenin hangi özelliğe daha çok etkisi olduğu paylaşılmıştır. Bu çalışma kapsamında topoloji optimizasyonu yapılmamıştır. İleriki çalışmalarda kütle optimizasyonu yapılarak özgün tasarımın birim kütle başına düşen mekanik özelliklerindeki belirgin artış hedeflenecektir.

Teknolojinin gelişmesiyle beraber artık malzemenin azaltılması, daha az enerji kullanılarak aynı final ürünün daha karmaşık geometrilerde elde edilmesinde olanaklar artmıştır. Tasarım belirlendikten sonra literatürdeki çeşitli malzemeler araştırılmıştır. Özellikle günümüzde eklemeli imalat açısından kolaylıkla üretilebilen malzemelerin seçilmesi hedeflenmiştir. Üretim yöntemi çeşitlerine ayrıca değinilmiştir. Eklemeli imalatla çeşitli üretim yöntemlerinin parametrelerinin son yapıya olan mekanik özellik etkisini değiştireceği vurgulanmıştır. Gelecekteki çalışmalarda özgün tasarımın numerik analiz sonucuyla test sonucunun araştırılması gerektiği vurgulanmıştır. Ayrıca üretim yöntemlerinin farklılıkları sonucu ortaya çıkacak farklı mekanik özelliklerin de araştırılması gerektiği belirtilmiştir.

Özgün tasarımın birim hücresi belirli parametrelerle tasarlanmıştır. Bu parametrelerin değişiminin etkisi ayrıca belirtilmiştir. Özellikle darbe uygulamalarında fayda sağlamak için birim hücre çeşitli yönlerde çoğaltılmış ve sandviç bir yapıda çekirdek özelliği göstermesi amaçlanmıştır. Bu tasarım adımları yapılırken NPR özelliği korunmuştur. Özgün yapının sandviç yapı içerisinde kullanılması ile hierarlik yapının birleşik yapı içerisindeki davranışını görmek amaçlanmıştır. Ayrıca gerçek bir uygulamada kullanılması durumunda (uçak kanat kesiti, koruyucu kask iç yapısı vs.) bu özgün hiyerarşik yapının ayrıca bu yapılarda modellenmesi gerekmektedir.

Özgün tasarım aşamasından sonra yapının mekanik özellikleri Sonlu elemanlar metoduyla (SEM) analiz edilmiştir. Nümerik analizler Ansys v2020 ticari yazılımı kullanılarak gerçekleştirilmiştir. Bu kapsamda çekme, basma yönlerinde yer değiştirmeler uygulanmıştır. Bunların sonucunda da kesitteki deformasyon yönü ve miktarı belirtilmiştir. Tüm bu nümerik çalışmalar karşılaştırmalı olarak grafiklerde sunulmaktır. Hesaplamalı modellerde çekme ve basma yönlerindeki etki kuvvet yerine yer değiştirme kullanılarak gerçekleştirilmiştir. Bu sayede yapıda belirgin deformasyonların oluşturulması sağlanmıştır.

Bunun yanı sıra özgün auxetic yapı içerisinde bulunan basma esnasında temas edebilecek yüzeylerde temas yüklerinin aktarılabilmesi için özel eleman tipleri tanımlanmıştır. Bunun sonucunda yapıda iç içe geçmeler engellenmiştir; gerçekçi sonuçlar elde edilmesi amaçlanmıştır. Ayrıca yapının darbe enerjisi sönümleme kapasitesi de incelenmiştir. Çeşitli hızlarda alınan darbe sonuçları neticesinde özgün yapının özgül sönümleme enerjisi ortaya çıkarılmıştır. Darbe analizleri sandviç yapıya ilaveten üst plaka hizasında 20 mm mesafede ek plaka ile gerçekleştirilmiştir. Bunun yapılmasının sebebi yapının enerji sönümleme esnasında çarpma ve geri sekme fiziksel durumlarının da yansıtılmak istenmesidir. Darbe analizi ile yüksek miktarda

şekil değişimi olması istemiştir ve gerçekte bu durumun olması halinde yapının feda edilmesi gerektiği ön görülmüştür.

Bu sonuçlar, yeni auxetic yapı-özellik ilişkilerinin yeni temel anlayışını ve potansiyel havacılık ve savunma teknolojisi ürünleri için hibrit petek yapılarının sağlanması açısından önem taşımaktadır. Özgün tasarımların ileride daha da yaygınlaşması beklenmektedir. Mühendislik tarihinde doğadan ve canlı yapılardan alınan ilhamlarla birden çok devrimsel buluşlara şahit olunmuştur. Doğayı taklit etmek özgün tasarımların yaratılması açısından bir intihal değil; aksine yeni buluşlara kapı açmak demektir. Bu tez çalışması kapsamında literatüre kazandırılmış olan özgün auxetic meta-malzemenin ileride matematiksel optimizasyon yöntemleri de kullanılarak yapının ağırlığının azaltılması ve mukavemetinde kayıp yaşanmaması amaçlanmaktadır. Optimizasyon sonucu yapıda karmaşık hierarşik yapının meydana gelmesi ön görülmektedir. Meydana gelecek hierarşik yapının katmanlı imalat yöntemleriyle üretilip test düzeneklerinde dayanımının ölçülmesi sonucu yapılan nümerik hesaplamaların da gerçekleştirilmesi amaçlanmaktadır.





1. INTRODUCTION

Engineering structures like airplanes, gas turbines, ship buildings, and automotive components are designed thinking the different type of loads that will acting on these structures through their life cycles. Human safety is an important role to create various structures. In these circumstances researchers are always keen on to put engineering safety factors for safe operations. By improvements on material science and manufacturing technologies safety factors are reduced, so costs of creating engineering components are also decreased. Not only the steady state loads but also transient loads are also crucial for the systems that need to have impact resistance capability. Impact situations could be seen in various mechanical systems. For example, gas turbine bird ingestion, car crash, helmet protection both defence industries and sport activities, and meteoroid crash for the space shuttles. There are variety of studies to evaluate harmful effects of impact results on people health and crucial components of the whole systems.

To obtain ballistic, crash, and blast protection sandwich panels with core fillings have been developing from past to present. Sandwich structures are capable of energy absorption for any sudden impact situations [1]. Cellular core structures are used mostly in sandwich panels as fillers. Basically aiming sandwich structures in impact energy applications is to obtain high stiffness ratios corresponding weights. The facesheet of sandwich structures are generally made of lightweight materials such as fibre-reinforced composites and aluminum alloys [2]. Although most of the time sandwich core structures are sacrificial at the time impact occurs, mechanical properties, design, and density of core structure has great importance to supply enough energy absorption. Core structures are generally produced by fiberglass composites, aluminum, and foam type materials. Thanks to great advancements in Additive Manufacturing (AM) technologies different type of materials (nickel based superalloys, steel, polymers etc.) could be building for the certain structures. Specifically, to obtain high amount of strain energy deformations metallic and polymer based materials are popular for high plastic deformation capabilities. For the

classification based on plastic deformations polymers and metallic materials could be shaped into different geometries. Especially for the impact related applications there are some specific cellular core shapes are used in the literature. Cellular core structures could be diversified as showed in Figure 1. According to figure cellular solids could be categorized two major classes as foams [4], and lattice structures [5]. The reason to categorize cellular solids into two groups is arising from being stochastic and/or hierarchical structures. Lattice and foam structures are used in aerospace, defense, automotive, and sports applications for the better mechanical results in case of any vibration control, static load carrying capabilities for multifunctional components, and impact energy absorption applications [6].

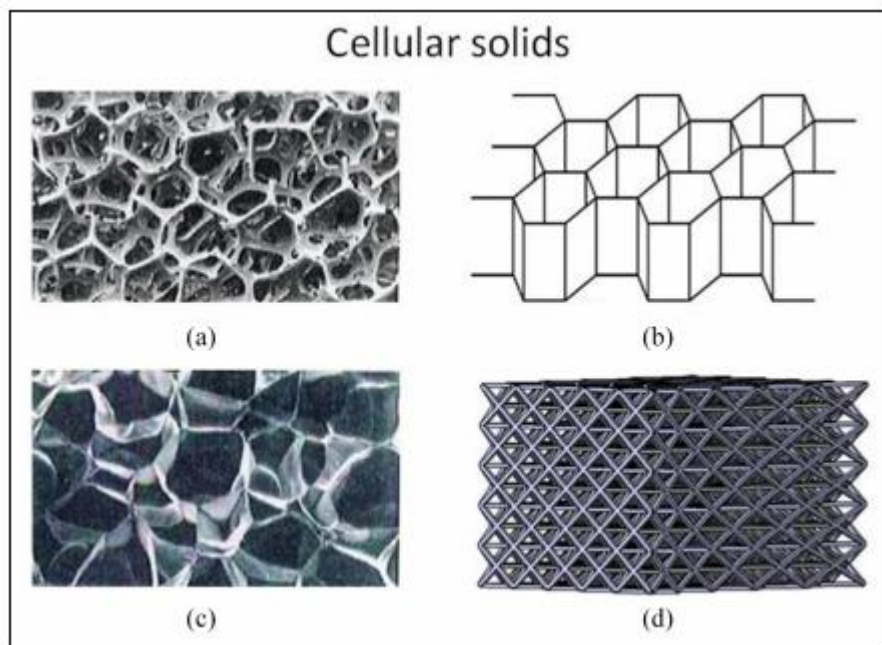


Figure 1: Cellular core structures [4,5].

The relationship between the crushing strength and geometric design parameters have been investigated by many researchers [7,8]. These studies imply that crushing and energy absorption properties could be enhanced by changing honeycomb structure geometry. For example, reducing edge length, changing cell angles and wall thicknesses will have an impact on crushing performances. In this context, various smart materials like shape memory alloys, and metamaterials have been developed.

Cellular core structures are mostly produced by conventional materials which have positive Poisson's ratios. Poisson's ratio is a measure of the expansion or contraction of a material in directions perpendicular to the direction of loading. In other words,

Poisson's ratio is the measure of the transverse strain relative to longitudinal strain. In recent years, researches on Auxetic metamaterials have been increased. Auxetic structures have negative Poisson's ratio (NPR) property which enables structures to have great energy absorption capabilities. Thanks to auxetic behavior, indentation resistance, fracture toughness and similar mechanical properties could be improved in case of cellular core usage for the sandwich structures. Designing novel auxetic materials and structures are still in development phase among the researchers.

1.1 Purpose of Thesis

Structures used in aerospace, defence, sports, and automotive industries have sandwich components with various type of cores to absorb energy for safe operations. Especially, high amount of strain needed areas use different kind of energy absorption designs to avoid vital consequences. Engineers tend to sacrifice these type of sandwich structures in case of emergent impact situations to gain high amount of energy dissipations. By the improving CAM and CAD technologies, engineers take advantage of design freedom phenomena. Since the last three decades' researchers focus on man-made designs that have negative Poisson's ratios [9]. Auxetic materials are the basically man-made materials that supply negative Poisson's ratio. Auxetic materials have gained an attention to absorb strain energies by sacrificing their initial structures. The most of the literature studies about auxetic structures usually adapted re-entrant, chiral, and rotating rigid structures.

The actual aim of this thesis study is to find a novel auxetic unit cell design and give an idea to researches for the future metamaterial designs. Besides this goal, mechanical properties of the novel auxetic sandwich core was analyzed by using FEM. NPR, compression, tensile properties and impact energy dissipation characteristics of the novel auxetic sandwich structure is also shared.

1.2 What is the Poisson's Ratio?

One of the characteristic properties of the material is the Poisson's ratio. The definition of Poisson's ratio is as follows: The unit strain that occurs in the normal direction of the force applied to a material and the unit strain rate in the direction where the force is applied is the Poisson's ratio. In the simplest definition, the Poisson's ratio is the

mathematical value of how much a material contracts or expands under compression or tension. Its symbol is denoted by ν and its formula is as in Equation 1.1.

$$\nu_{21} = \frac{-\varepsilon_1}{\varepsilon_2} \quad (1.1)$$

ε_1 : Unit strain perpendicular to the applied force

ε_2 : Unit strain in the direction of the applied force

When the materials in nature are examined, it is seen that the Poisson's ratio is generally positive. In other words, one of the natural characteristics of materials is the Poisson's ratio and this ratio is defined as positive. Otherwise, this ratio does not exceed 0.5 numerically. Figure 2 shows the deformation of the vertical axis (2) as a result of the application of tensile force on the normal axis (1) to a material with positive Poisson's ratio. The rectangular structure shown with thin lines in Figure 2 is the view of the original material without deformation. The shape that the structure takes after the deformation caused by the tensile force is indicated with thick lines [10].

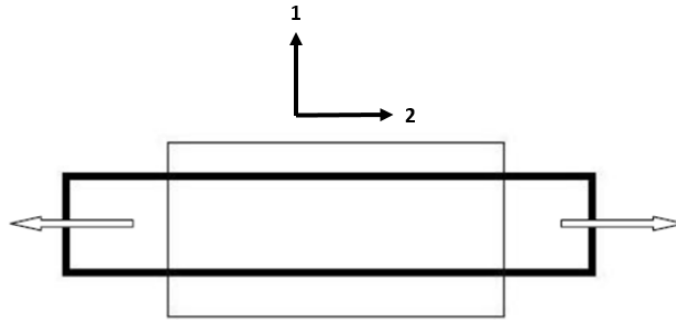


Figure 2: Tensile force acting on material with a positive Poisson's ratio [10].

Materials with negative Poisson's ratio are also defined as “Auxetic” metamaterials in the literature. The emergence of the NPR has been made by making new designs as needed. There was a need for designs that would create “opening” when exposed to tensile strain and “closure” when exposed to compression strain, depending on the areas of use and usage conditions. When this feature is combined with the needs such as high strength, low density, high energy absorption capability, studies on porous structures have increased and structure designs with negative Poisson’s ratio have gained importance. Figure 3 shows the deformation of the vertical axis schematically

as a result of the application of tensile force on the horizontal axis to a material with negative Poisson's ratio.

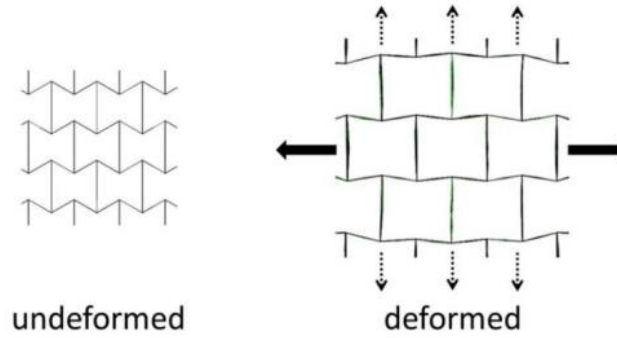


Figure 3: NPR behaviour of re-entrant auxetic structure under tensile strain [11].

As can be understood from the Figure 3 representation, in the materials with negative Poisson's ratio, opening occurs in the direction perpendicular to the tensile force [11]. If materials with NPR are need to be classified; It is divided into natural and man-made materials. At this point, it should be noted that the vast majority of materials with negative Poisson's ratio are man-made materials, in other words, artificial materials. However, there are also materials in nature that have NPR.

In many different applications, porous and hierarchical structures with negative Poisson's ratio are preferred. Biomechanics and aviation / space industry are the two most important areas that provide use today. Prostheses used in biomechanics can function as close to nature as they have a negative Poisson ratio, depending on the area of use and the requirements expected from the prosthesis. Likewise, with the needs that have accelerated in the aviation and especially the space industry in recent years, materials with NPR can have priority to use.

The reason why structures with negative Poisson's ratio have the potential to be used in many areas is that some of their properties are superior to other materials. Some of these features are the shear modulus (G) is much higher than the Bulk modulus (K), high indentation resistance, high damping and absorption ability [12-14]. In the following sections, some of these properties are discussed.

1.3 What are Auxetic Materials?

Auxetic materials are the materials with negative Poisson's ratio. The negative values of Poisson's ratio are arising from geometrical shape, and still development phase with

advanced manufacturing techniques. Auxetic materials increase popularity thanks to their different positive novel properties, like shape memory applications, energy absorption fields, and vibration control critical structures. The term “auxetics” was first used by K. E. Evans from Greek word “auxetos” which means “that maybe increased” [15]. Auxetic materials take place in a variety form as micro and macro structures. Based on deformation mechanism, this structures can be categorized into three groups: A) re-entrant type; B) chiral type; C) rotating (semi-) rigid structures. Figure 4 could give better understanding of the auxetic structure shapes.

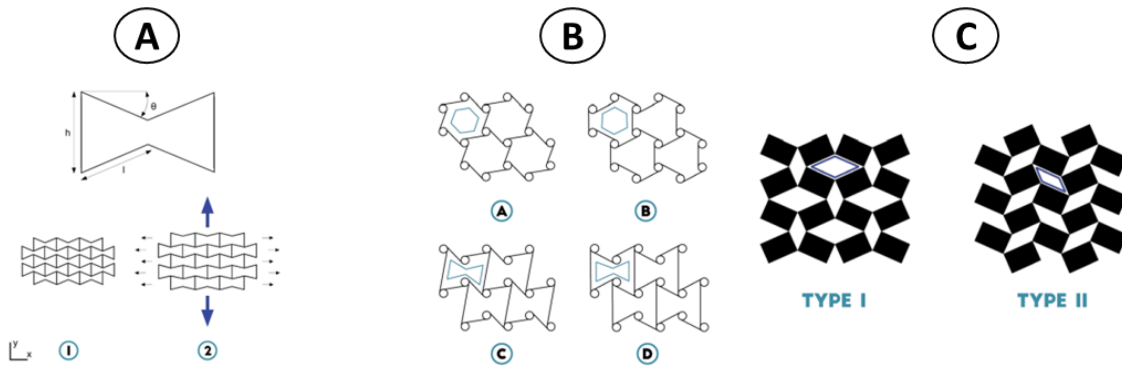


Figure 4: Auxetic metamaterial structure shapes [9].

Re-entrant basically advert to something that will direct to inward which exactly having a negative angle. Re-entrant shape is illustrated in Figure 4. The most of the literature reviews have focused on the re-entrant type auxetic structures. Poisson’s ratio characteristics of re-entrant structures highly depend on the angle between unit cell ligaments.

A typical chiral shaped auxetic unit cell represents a central circular, or cylindrical unit with tangentially merged ribs and/or ligaments. The principle mechanism of chiral structures is rotating under mechanical loadings, and then supporting ribs stretches or contracts. Chiral structures have also rotational symmetry. Opposite to re-entrant structures, chiral structure Poisson’s ratio does not depend on the angle between sub-units. Increasing the number of supporting ribs per circular center unit may increase the stiffness of the whole structure assembly.

Rotating (semi-) rigid structures will be the last category of the auxetic structures in terms of deformation mechanisms. Simplified rotating structure includes rigid squares or circles moving through the load vector applied on the body. While loaded in tensile or compression directions, these structures will be responded as either in expansion or

contraction. Beyond the novel mechanical characteristics of auxetic materials like vibration damping, compression and tensile resistance; indentation resistance is also another gaining point. Auxetic materials provide more resistance to indent than other materials with lower plastic deformation. Figure 5 shows that the Auxetic material is more likely to flow towards to indentation point, and other materials tend to avoid from the load applied [16].

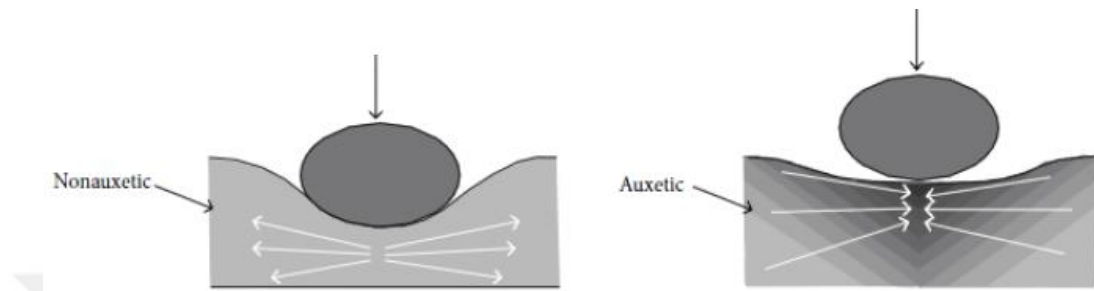


Figure 5: Indentation behaviour of nonauxetic and auxetic materials [16].

In conventional materials, material density decreases just below the impact point affected by the sinking load. In other words, the material in this area spreads around due to the positive poisson's ratio. In auxetic materials, this situation will be the opposite, since they have a negative poisson's ratio. In other words, material density will increase in the part just below the impact point where the load affects. Due to the increase in density in this region, the hardness of the material will increase and consequently the sinking resistance will also increase [17].

1.3.1 The history of auxetic materials

Although international developments on auxetic materials were more visible in the 1991s, Roderick Lakes was the frontier to use NPR for the first time in metallic structures in his work [18]. In the early 1900s, German physicist Woldemar Voigt in his experimental work on iron pyrite described a material with a negative Poisson Ratio and presented a single cubic crystal pyrite sample with a Poisson Ratio of -0.14. In his work, he observed that the crystals expand in the same direction somehow when stretched sideways. Voigt was unable to explain this original behavior and could not anticipate possible applications for this feature at that time, and it was ignored for decades. Voigt suggested that this effect may occur as a result of crystal twinning.

In the late 1980s, researchers produced foam with auxetic properties from a commercial foam. This great improvement has shown that a conventional material has

been given auxetic properties thanks to its own designs [19]. With this development, researchers realized that materials with auxetic properties have many applications. The main classification of synthetic auxetic materials produced since then are metals, ceramics, polymers and composites [20]. Natural auxetic materials are also available, such as arsenic crystal, cadmium crystal, α -cristobalite and many cubic elemental metals. Moreover, some biological materials such as cat skin, salamander skin, cow udder skin are naturally auxetic [21].

The mechanism of auxetic materials depends on the micro or geometric structure and deformation mechanism when force is applied to these structures. When force is applied to the auxetic material or structure in one direction, they flex in the perpendicular direction and exhibit a negative Poisson's Ratio [22].

When force is applied, the internal structure of the material, geometric shape and the type of deformation cause the formation of auxetic behavior. Although auxetic materials have been known for more than 100 years, they have attracted more attention again since the late 1980s.

Until today, many different auxetic materials have been produced such as polymers, metals, ceramics, composites, coatings and fibers. Figure 6 shows the historical development of the auxetic materials year by year [23].

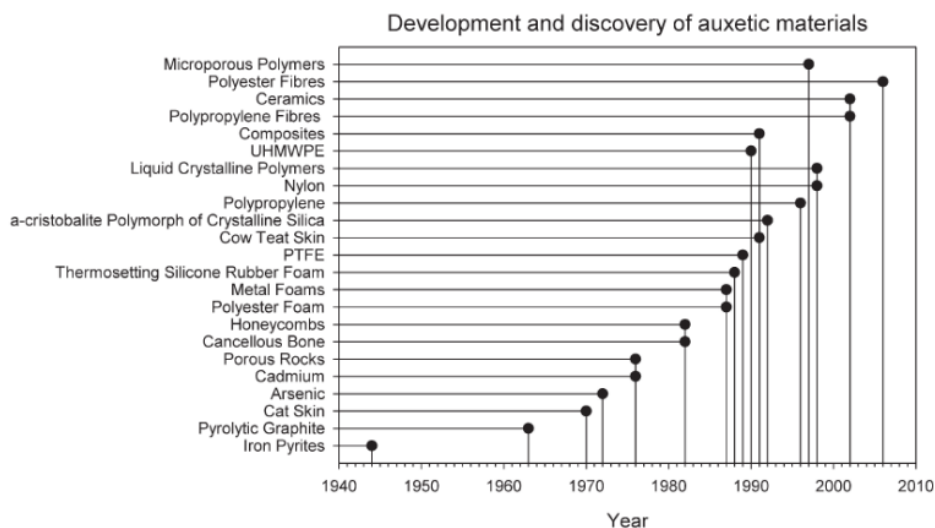


Figure 6: Historical development index of auxetic materials [23].

1.3.2 Properties of auxetic materials

Due to the novel characteristics of Auxetics some of the mechanical properties make these structures one step frontier than other hierarchical materials and structures. Some of these mechanical properties can be categorized as indentation resistance, shear strength, synclasticity, fracture toughness, and vibration transmission.

1.3.2.1 Indentation resistance

Auxetic materials are gaining attentions thanks to their high performance on the indentation resistance. In materials science, indentation resistance or hardness means that measurement of the resistance under the local indentation from resulting pressure applied by specific tool. Generally, NPR gives a positive result for the material hardness in the elastic deformation region [16]. For many years' indentation resistance have been measured by the method of Ball Indentation Test. Theoretically, hardness for isotropic materials is proportional to $[(1 - \nu^2)/E]^{-1}$ where ν denotes to Poisson's ratio, and E stands for Young's Modulus. According to classical elasticity theory ν is between $-1 \leq \nu \leq +0.5$ for the isotropic materials [16].

1.3.2.2 Synclasticity

Shape deformation is another novel characteristic of auxetic formed structures. When bending moment applied on these type of structures, they act as different results compared to conventional core structures, like honeycombs. Representation of shape deformation of both auxetic structure and honeycomb structure is shown in Figure 7. After bending, auxetic structure results in dome shape; honeycomb structure shows saddle shape. This property called as Synclasticity [15]. Thanks to synclastic behavior auxetic structures are prone to be used in protection dominant area, like defence, sports applications, and safety important devices.

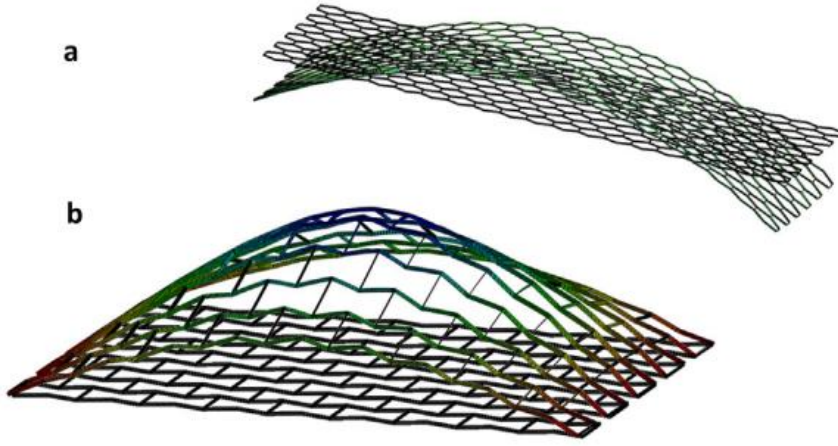


Figure 7: Bending deformation of a) non-auxetic and b) auxetic materials [15].

1.3.2.3 Shear properties

Auxetic materials have good resistance as a result of their negative Poisson's ratio property. Isotropic materials have two basic elastic constants that could give mechanical properties of material. They are listed respectively as Young's modulus (E), and Poisson's Ratio. Additionally, bulk Modulus (K) and shear modulus (G) are derived from the two basic constants. The equations are given below gives relation between those constants.

$$G = \frac{E}{2(1 + \nu)} \quad (1.2)$$

$$K = \frac{E}{3(1 - 2\nu)} \quad (1.3)$$

According to abovementioned equations, it could be seen that approaching values of Poisson's ratio to -1, shear modulus (G) becomes infinite. Therefore, it is observed that auxetic materials have better properties compared to non-auxetic materials. Based on the study carried out by Evans, it is reported that among the all auxetic structures chiral auxetics with small rings have greater shear modulus than other auxetics which have bending dominated characteristics [15].

1.3.2.4 Fracture toughness

Re-entrant auxetic structures have improved fracture toughness properties. According to Choi and Lakes's study, it is observed that re-entrant auxetic foams have good

fracture toughness; despite their low Young's modulus. Below equation represents the comparison of the fracture toughness for re-entrant and conventional foams [24].

$$\frac{K_{IC}^r}{K_{IC}^*} = 0.53 \frac{\sqrt{1 + \sin(-\theta + \frac{\pi}{2})}}{1 + \cos 2\pi} \quad (1.4)$$

Above expression the term K_{IC} denotes for the fracture toughness. The superscripts r and * means re-entrant and conventional respectively. The angle θ denotes for the cell rib angle. The cell shape is basically represented by the angle of θ parameter.

1.3.2.5 Wave propagation / vibration transmission

In nature, vibration and sound are the form of wave propagations. The properties of these waves like velocity and absorption are depending on the way they are moving through. For example, sound propagation in water and air have different physical properties. Based on this brief definition, wave propagation is also affected by the structures. In this context periodic, cellular, and hierarchic structures play a vital role to direct and/or guide the wave propagations in the forms of vibration or sound. The frequency of the wave is determined by the period density and material properties of the core structure. Assuming that the all the material properties are same for auxetic and non-auxetic materials it has shown that auxetic materials have 10 times better absorption when compared to non-auxetic structure foams [25]. During elastic wave propagation frequency band types can be categorized into two groups which are allowed propagation (known as pass bands) and restricted propagation (band gaps or stop bands) depending on the periodicity of the structure. Studies carried out by taking into account the trichiral lattice structures to show the important attenuation in the frequency range for the related band gap during vibration transmission [26].

1.3.3 Auxetic materials in nature

Various studies reported that many auxetic forms are located in the nature. The first study that NPR evidence has carried out by Love [27]. Furthermore, it has been published that the important amount of the cubic structured metals has auxetic behavior while stretching them through [110] direction [28]. Molecular auxetic structures were also studied by Nkansah et al; in this study negative Poisson's ratio behavior was seemed in benzene rings and acetylene groups [29]. In Figure 8, the

molecular compound reflexyne structure is showed for its re-entrant auxetic shape visualization.

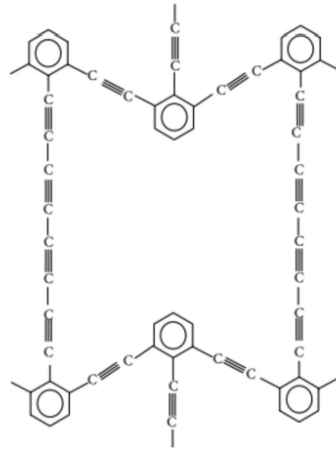


Figure 8: (1,4) reflexyne re-entrant auxetic structure molecular shape [29].

Furthermore, important research was also conducted by Grima et al [30]. In this research, de-wrinkling mechanism and voids inside the graphene were found as a result of wrinkled sheet of paper. This mechanism causes an auxetic behavior. In Figure 9, different strain levels are applied on graphene sheet of wrinkled paper to show negative Poisson's ratio results.

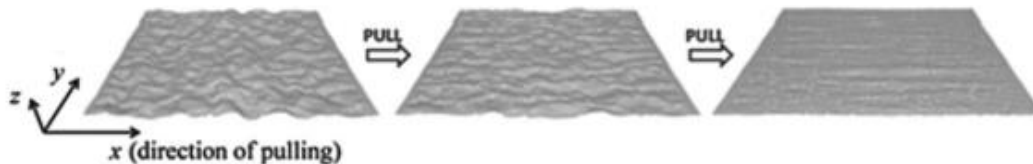


Figure 9: De-wrinkling mechanism behavior to graphene sheet [30].

1.3.4 Application fields of auxetic materials

Improvements in engineering design, new material development, and optimizing manufacturing techniques always serve to new advancements in various topics. Human and other living creature's health is one of the major motivation behind the advancements in engineering research. In this thesis auxetic structure developments are briefly put into together, and novel auxetic structure design is shared in the following subjects. Auxetic structure applications are spread into different categories. Therefore, within this subject medical & biomedical applications, sports applications are selected as major topics of application areas of auxetic structures.

1.3.4.1 Medical and biomedical applications

The most important property of auxetics is NPR. Having property of expanding in cross section while stretching, and shrinking while compressing is crucial for some of the medical applications. Thanks to auxetic behavior some surgeon operations have successful results. For example, human veins can be lost its function in case of age, and some other health problems. For this reason, a mechanism need to be developed that can give resistance to vein walls against to vein cross section area decrease; so stent application is one of the most popular medical application that shows auxetic behavior. Bhullar et al. [31] studied on rotating semi strucures, which is a one of the major type of auxetics, for medical stent applications. Figure 10 shows developed rotating auxetic structure system for the stent application. After it has been located into the veins, it responds as stretching behavior to utilize vein function.

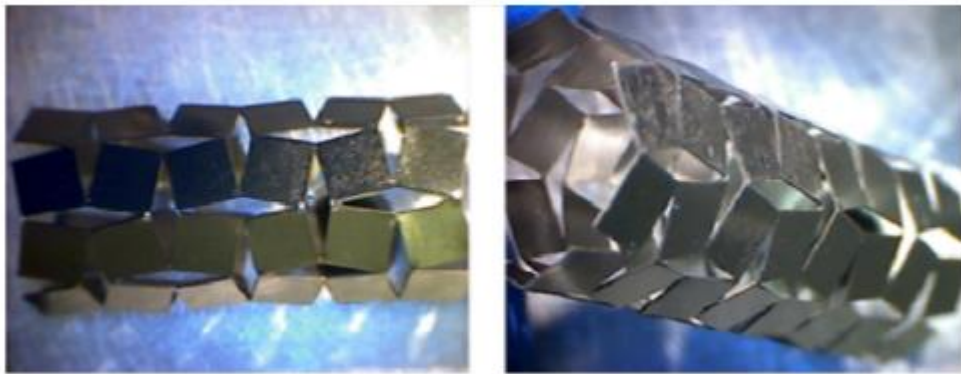


Figure 10: Microscopic image of stent with rotating auxetic structure property [31].

Also the material of medical stent application is crucial, because of the prohibition of inflammation. To avoid this kind of problem multimaterial auxetics could be developed by using advanced manufacturing techniques. This multimaterial property may also give an opportunity to manufacture low cost products.

The tissue engineering is also another popular topic in research fields. Composite structured auxetics can be used instead of human skin that creates nonlinear stress-strain reactions. This biomedical inspiration can be realized by hierarchical layer arrangement of auxetics. Also, K. E. Evans and A. Alderson mentioned that artificial blood veins can be manufactured in the form of auxetic structure to prevent rupture and/or damages from outsource [16]. In Figure 11, non-auxetic blood vessel and auxetic blood vessel effects are shown.

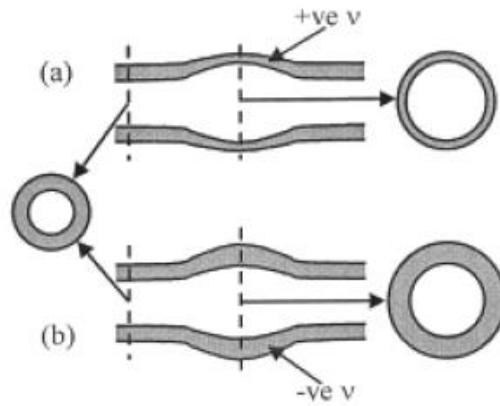


Figure 11: a) Nonauxetic bloodvessel b) auxetic blood vessel [16].

In this case, non-auxetic blood vessel tends to decrease the wall thickness. This will lead to open blood vessel in case of pumping the blood. This may lead a crucial failure that could end with death of patient. However, in auxetic vessel case, blood vein is opened by pumping the flow without decreasing the vessel thickness.

1.3.4.2 Sports applications

The human body is fragile for the impacts that is coming from outsources. Especially, human head is the most vulnerable part, as any impact to the head will result in severe injury or death. In this circumstances, helmets are designed to protect human health during sport competitions. Specifically, Traumatic Brain Injury (TBI) is the most common severe damage after head impacts. The importance level of brain injury basically depends on the sport category. For example, cycling, motor racing, alpine sports, and American football are prone to be head injuries. Besides, projectile based sports like ice hockey, baseball, cricket have severe possibility of injuries both head and face.

According to research that is reported by Centers for Disease and Control Prevention (CDC) there is a growing percentage, which is %62, to visit emergency room due to the brain injuries [32]. Figure 12 shows the distribution of the professional sport branches that cause emergent injuries.

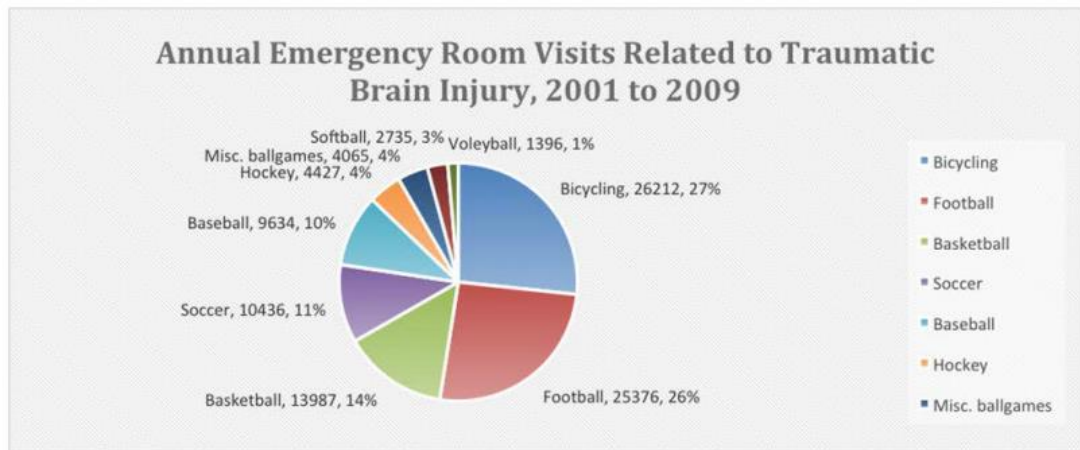


Figure 12: Emergency room visit related to TBI between 2001-2009 [32].

Head covering accessories are the most important parts to protect severe brain injuries. As a result of, the helmet design and engineering play a vital role for human health. Auxetic materials have potential for the usage as a core structure of the protective equipments such as helmets. There are other parameters for accessory design for the professional sporters. The performance is an important engineering restriction to design equipments. Because, everybody tries to avoid heavy weights to achieve better performances. Auxetic structures can be a good alternative for supplying both energy absorption property and light weight as well.

1.3.4.3 Defence applications

As in sports applications, auxetic materials have gained importance in this field in terms of protecting human safety and health. It is possible to replace existing materials and designs with the high stiffness rate per unit mass brought by auxetic materials.



2. SANDWICH STRUCTURES AND MANUFACTURING METHODS

Sandwich structures are widely used in aviation, maritime, shipping and defense industries because of their unique advantages such as hardness and strength, lightness, high energy absorption capacity and being able to be produced for different purposes. Sandwich structures are defined as a three-layer material structure consisting of two thin layers of high strength and a middle layer of low to medium strength and density. A general sandwich geometry is shown in Figure 13 below. The two thin layers usually consist of thin, hard and strong materials. The middle layer is the core of the sandwich and is thick, lighter and weaker.

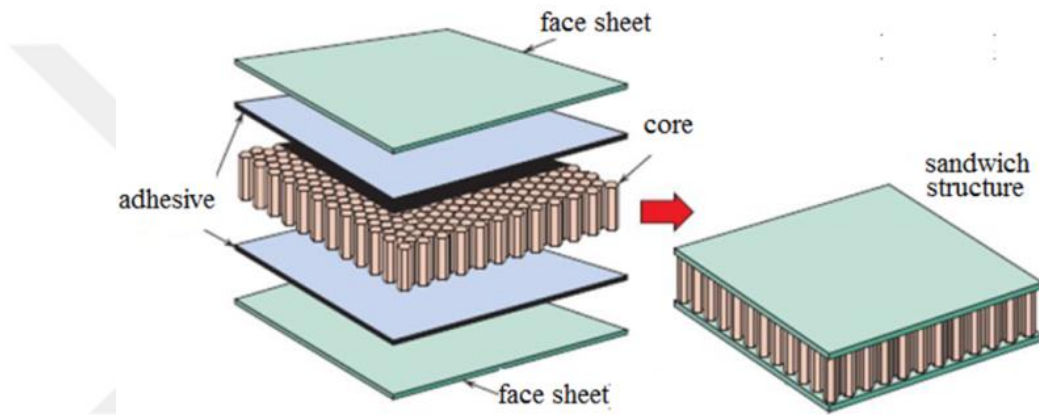


Figure 13: Typical sandwich structure illustration [34].

Sandwich structure plays an increasingly important role in structures due to the extremely high bending stiffness / weight ratio compared to monocoque (thin wall structure) and other architectures. As a result, the sandwich structure has great advantages due to lower lateral deformations, higher buckling resistance and higher natural frequencies compared to other structures. Therefore, for a given mechanical and environmental load conditions, the sandwich construction can generally exhibit much superior properties with a lower structural weight than other configurations [34].

2.1 General View of Sandwich Structures

The core of a sandwich structure mainly serves to separate, support and stabilize the face layers so that the desired bending stiffness is achieved. In almost all cases, the core bears the actual out-of-plane or transverse shear loads in a sandwich shell or panel structure. Other functions such as heat and sound insulation are also highly dependent

on core material properties. In all sandwich structures, in-plane and bending loads (primary loading) are carried by the face layers and the core bears transverse shear loads. Generally, the face layers are the same in material and thickness. So the variety of sandwich structure types mainly depends on the configuration of the core [35]. Core materials are generally divided into four main types. These are honeycomb core structures, corrugated core structures, foam core structures and lattice core structures.

2.1.1 Honeycombs

The honeycomb core is very similar to the honeycombs found in nature and made by bees to produce honey. Honeycomb core is also called cellular nucleus or open cell nucleus. In principle, although they are produced in many different geometries, the most widely known are hexagonal honeycomb structures shown in Figure 14 below. This hexagonal geometry of the structure provides such structures with low density, high out-of-plane compression strength and high out-of-plane shear strength [36].

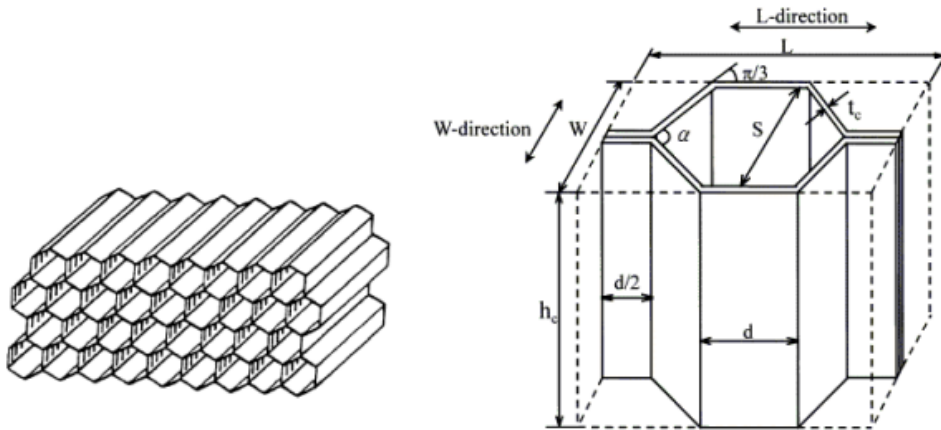


Figure 14: Honeycomb structure geometry [37].

The honeycomb core cell size is determined by the diameter of a circle that can be drawn tangent to the inner walls of a cell. Figure 15 shows the strip length (L), width (W) and thickness (T) for a typical hexagonal honeycomb core. The cell configurations that can be obtained from a given sheet material are limited by its thickness and stiffness.

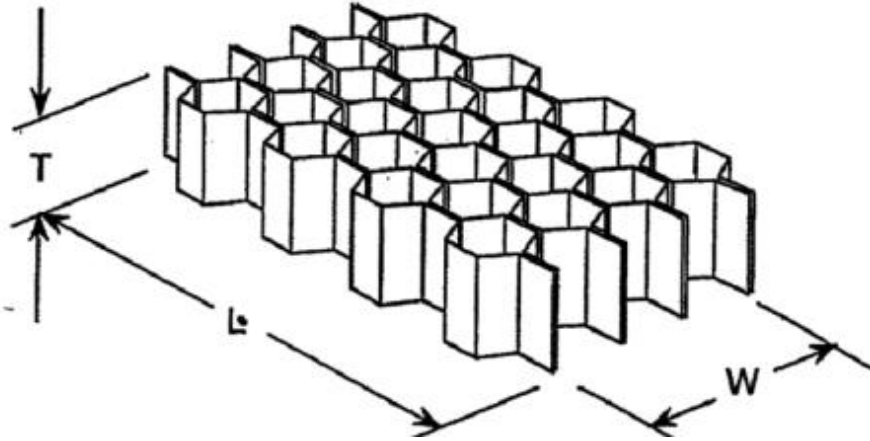


Figure 15: Honeycomb core structure strip direction [38].

Honeycomb cores for sandwich making are routinely made from thin aluminum alloys, resin-treated fabrics, resin-treated paper, stainless steel alloys, titanium alloys, and plastics. The honeycomb core structures most commonly used today are still Aluminum-based ones. Non-metallic honeycomb structures are commonly composed of glass fiber reinforced composite materials, paper, and Kevlar material, also known as Nomex. As the interest in polymeric materials has increased in recent years, it is ensured that materials in traditionally used areas are also produced from polymeric materials. For this reason, polymeric honeycomb structures, especially thermoplastic polymeric honeycomb structures, have been included in the group of non-metallic honeycomb structures with a growing area of use.

2.1.2 Corrugated core structures

One of the most preferred practical core topologies in high-strength sandwich panel construction is the corrugated core. These cores provide high strength as well as manufacturing advantages in both normal and longitudinal directions of the structures. These types of cores are essentially the intermediate form used in the construction of honeycomb core structures. For this reason, it is one of the most important advantages that they can be produced much more easily than honeycomb core structures. In addition, these types of core structures are preferred due to their high energy absorption capabilities, especially under explosion and high-speed impact loading. For this reason, it is used in military areas exposed to more explosive loads, in places where there is a risk of explosion, on ground and lateral walls and in liquid-gas transport tanks. Corrugated core structures are commonly produced in triangular, trapezoidal,

square and sinusoidal geometries. The schematic representation of these structures is shown in Figure 16 below; Triangle(a), Trapezoidal(b), Quadrilateral(c), Sinusoidal(d).

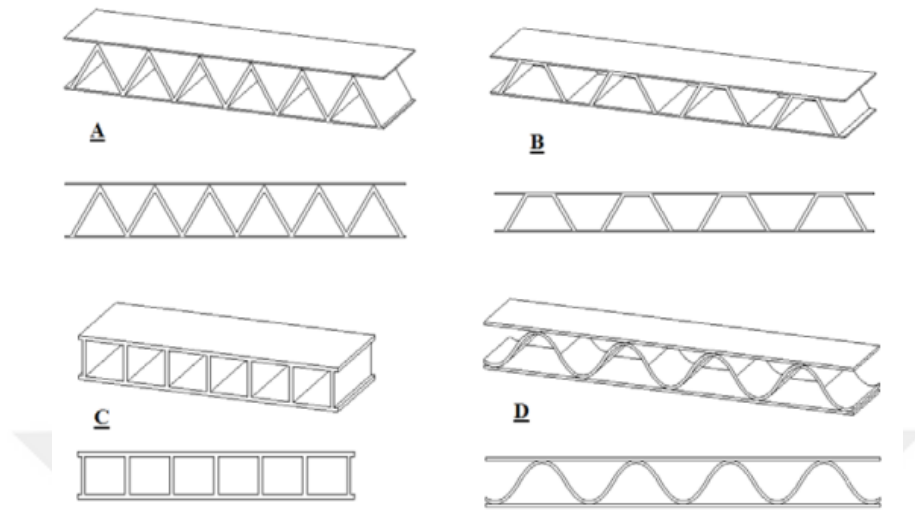


Figure 16: Sandwich structures with corrugated cores [Anonym].

One of the main differences between honeycomb structures and corrugated structures is the longitudinal and perpendicular use differences in their use as a core structure. As it is known, honeycomb structures are placed in such a way that their pores are closed by the face layers in order to provide rigidity and high strength to the structure. The opposite is true for corrugated core structures. This application difference provides the following two advantages to corrugated cores; The first one is the energy absorption capability of the building with the plastic deformation property and the other is the ventilation mechanism that the structure gains thanks to the groove channels formed throughout the structure, so that the building has a moisture-repellent characteristic [39].

2.1.3 Foams

Foam cores have been developed to overcome the main disadvantages of natural (wood or paper) core materials, particularly undesirable changes in density and moisture absorption. Plastic cores are foamed, expanded or otherwise processed to reduce the apparent density of the plastic to a practical range for the core material. The desired core properties can be obtained by controlling the expansion process for these cores. Metallic foamed cores can be produced by mixing molten aluminum-magnesium alloys with suitable blowing agents and cooling the mixture to form a porous solid. In

addition to these materials, glass foams can be produced. Although this type of core material is not as strong or hard as honeycomb core of the same density, it offers the following advantages:

- Core joint elimination,
- Thin and even joining layer between face layers and core,
- Use of pre-molded, void-free face sheets that can be easily checked before assembly,
- Good electrical properties and flexibility in manufacturing.

Foam core structures made of different geometries are shown in Figure 17 below.

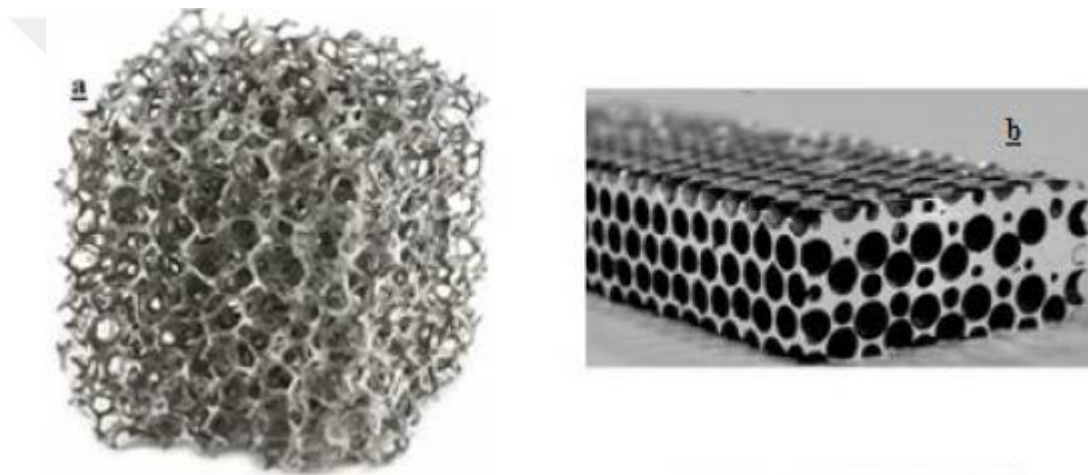


Figure 17: Different foam structures a) open-foam structure b) closed foam [41].

2.1.4 Lattice core structures

This core generally offers users the combination of structural performance and potential multi-functionality. Lattice core structures can be in a wide variety of geometries. The most known and widely used ones are tetrahedral, pyramidal and 3D kagome structures given in Figure 18 below. The beam members of the lattice structures are topologically structured to resist predominantly axial stress (tension and compression) when sandwich panels are loaded by bending stress. Thus, the sandwich panel will only be exposed to axial deformations.

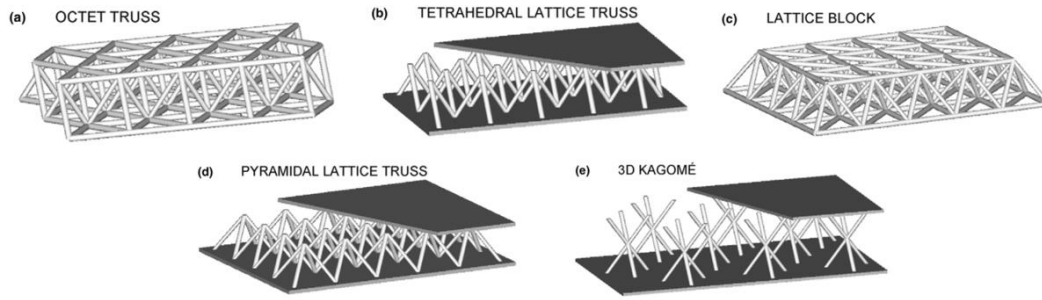


Figure 18: Different lattice core geometries: a) Octet b) Tetrahedral c) Lattice d) Pyrimidal Lattice e) 3D Kagome [42].

Lattice beam structures are gaining more and more attention as they have combinations of mechanical, thermal and acoustic properties that provide potential opportunities for a variety of multifunctional structural applications. Lattice materials offer ultra-light structures with high specific strength and high specific strain, high positive and negative Poisson's ratio, excellent impact absorption, acoustic insulation, and suitability for use as heat exchangers [43].

Various properties of lattice structures and foams are widely used when creating sandwich structures. In many applications, a deterioration of the sandwich structure occurs as the core structure is damaged by the shear load. On the other hand, it is desirable that sandwich structures exhibit greater energy absorption and proper bending when subjected to bending moments. The auxetic structures can potentially provide all these advantages, making them ideal candidates for core structures.

Auxetic structures can potentially be used in large-scale structures. The superior stiffness of the auxetic structure makes them desirable structures in the design of bridges and high-rise buildings, sport applications, and military areas. Currently predominant structural designs are based on triangular geometry due to its stiffness and stability. However, the triangle is not the most efficient mesh structure design in terms of overall performance. The characteristics of the auxetic structures can lead to the solution of this dilemma.

2.2 Mechanics of Sandwich Structures

Some typical advantages of sandwich structures include high rigidity and specific strength, vibration and high energy absorption capacity, good thermal and acoustic insulation, etc. features are included. A major disadvantage is that most core materials,

such as low density polymer foams, have relatively low transverse flexibility. Therefore, it tends to exhibit some unique initial damage modes such as facial wrinkling and local indentation, especially under localized loads.

This is a situation that should be carefully evaluated by the designers. This is because there are some typical situations where a sandwich material can experience severe loading conditions in complex junction areas, including the emergence of highly concentrated loads, which are quite common due to low-velocity impact loading from external objects during transport or use to which many transportation structures are exposed. The most common damage modes in planar sandwich beams are shown visually in Figure 19 below; facial layer flow/breakage(a), core shear damage(b), wrinkling(c&d), general buckling(e), shear curl(f), facial layer pitting(g), local core indentation(h).

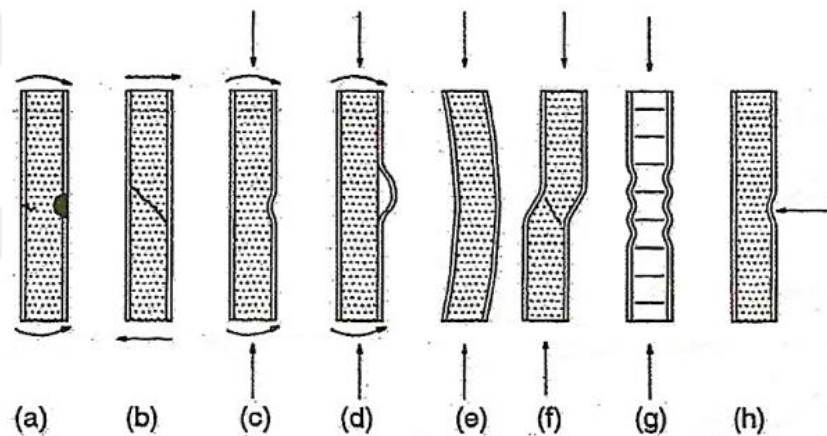


Figure 19: The most common damage modes of sandwich beams [44].

This section will focus on the basics of the planar sandwich beam theory. This theory, which is almost the same as the engineering beam theory, will have to take into account the transverse shear deformations differently. This theory is often referred to as the Timoshenko Beam Theory. Another innovation from engineering beam theory is that different loads will be carried by different parts of the structure. The theory given here is a brief summary of what was thoroughly described by Allen and Plantema (1966) [45]. For simplicity, the unit width of all beams i.e. loads, stiffness, etc. values will be given per unit width. The "f" index will be used for the face plates, while the "c" index will be used for the core.

2.2.1 Bending rigidity

The basic problem of a straight beam subjected to a constant bending moment that gives the beam a curvature (k_x) (the inverse of the radius of curvature (R)) is given below in Figure 20.

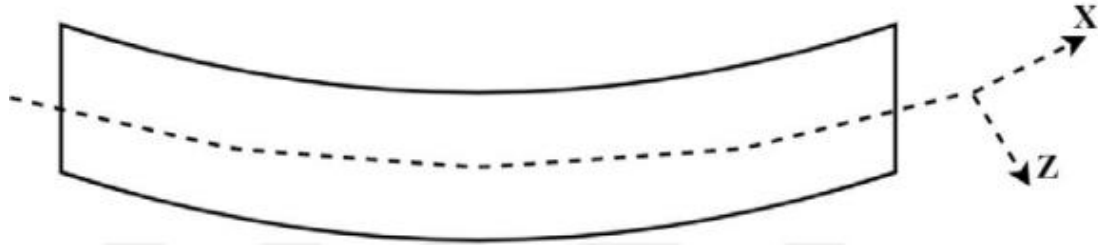


Figure 20: A beam subjected to bending moment [45].

The strain value in an area z away from the neutral axis can now be expressed as:

$$\varepsilon_x = k_x \cdot z \quad (2.2)$$

So it changes linearly with z . The bending moment expression that should be applied to cause the curvature of k_x :

$$M_x = \int \sigma_x \cdot z \cdot dz = \int \frac{E \cdot z^2}{R_x} dz = k_x \cdot \int E \cdot z^2 \cdot dz = \frac{E \cdot I}{R_x} \quad (2.3)$$

If the expression bending stiffness is drawn from here:

$$E \cdot I = \int E \cdot z^2 \cdot dz = D \quad (2.4)$$

The term EI is the bending stiffness where elastic modulus is E and the moment of inertia is I . From now on, when Young's modulus E changes along its z -coordinate, then EI will now be called D as it cannot be removed outside of the integral in equation 2.3. Hence, the definition of moment of inertia is lost. Therefore, for a general cross section, equation 2.3 should be used as given and bending stiffness (D) will be the only well-defined property. Thus, the last valid expression for strain will be as follows:

$$\varepsilon_x = \frac{M_x \cdot z}{D} \quad (2.5)$$

Thus, the strain still varies linearly with z on the cross section. The basic equations have been established, we can begin to calculate the cross-sectional properties and

stresses within a sandwich beam. First, let's define the coordinate system and the positive directions for loads as in Figure 21.

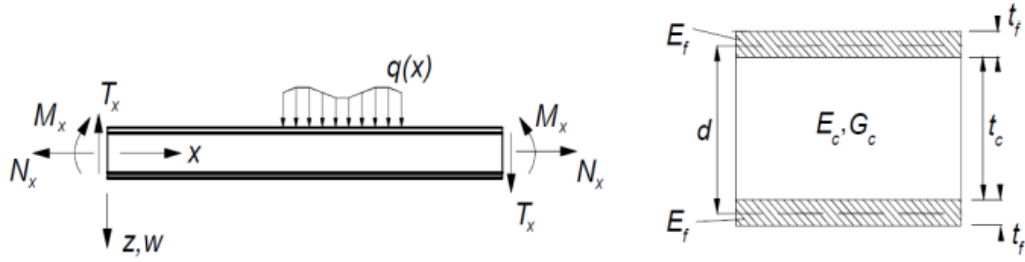


Figure 21: Determination of Signs for Sandwich Beam [44].

In order not to complicate the analysis at this stage, let's assume that the sandwich has a symmetrical arrangement, that is, the elastic modulus E_f will be the same since the faces have the same thickness t_f and are made of the same material. The thickness of the core is taken as t_c and the elastic modulus as E_c . Bending Stiffness (D) then takes the following expression for a section like in Figure 22:

$$D = \int E \cdot z^2 \cdot dz = \frac{E_f t_f^3}{6} + \frac{d^2 E_f t_f}{2} + \frac{E_c t_c^3}{12} = 2 \cdot D_f + D_0 + D_c \quad (2.6)$$

In this equation, $d (t_f + t_c)$ is the distance between the centers of the faces. The first term corresponds to the bending stiffness of the faces tilted around their individual neutral axes, the second to the stiffness of the faces associated with bending around the central axis of the entire sandwich, and the third term to the bending stiffness of the core.

The faces are generally thin compared to the core, i.e. $t_f \ll t_c$ and the first term of equation 2.5 is therefore quite small, and if less than 1 percent of the second term the following expression is used:

$$3 \cdot \left(\frac{d}{t_f} \right)^2 > 100 \text{ or } \frac{d}{t_f} > 5.77 \quad (2.7)$$

As a result of the material selection, the core usually has a much lower modulus than that of 100, i.e. $E_c \ll E_f$. Hence, the third term in equation 2.5:

$$\frac{6.E_f.t_f.d^2}{E_c.t_c^3} > 100 \quad (2.8)$$

Thus, for a thin walled sandwich structures, $t_f \ll t_c$ and a weak core, $E_c \ll E_f$, the bending stiffness can be written approximately as:

$$D = \frac{E_f.t_f.d^2}{2} \quad (2.9)$$

For ordinary engineering materials used in sandwich making, the core / face thickness ratio is commonly in the regime of 10 to 50 and the face / core modulus ratio between 50 and 1000. An important fact to be noted is that the dominant term in the expression for bending stiffness is the term for the faces tilted around the neutral axis of the entire sandwich. The fact that the bending stiffness of a sandwich consists mainly of the part caused by the interaction of the components is often referred to as the sandwich effect.

2.2.2 Sandwich effect

Now the consequences of the above results can be investigated. Consider that a beam of a homogeneous material with a certain Young's modulus, E and a certain strength is subjected to bending moment. Suppose that calculating the weight, bending stiffness and strength of the beam according to the above equations and cutting the same beam into two halves and separate the parts with a core. Given these steps, it is now possible to calculate the corresponding stiffness and strength of sandwich beams and the relative properties given in Figure 22 will be found.

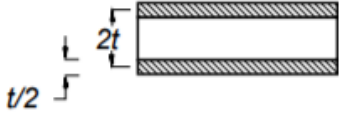
	Weight	Flexural rigidity	Bending strength
	1	1	1
	~1	12	6
	~1	48	12

Figure 22: Comparison of homogeneous and sandwich cross sections [44].

2.2.3 Equivalent width method

Another way to analyze a sandwich is to treat the sandwich structure by viewing it as an I-beam and it is done as follows. Considering a sandwich structure of width b as shown in Figure 23 below as an I-Beam of width b .

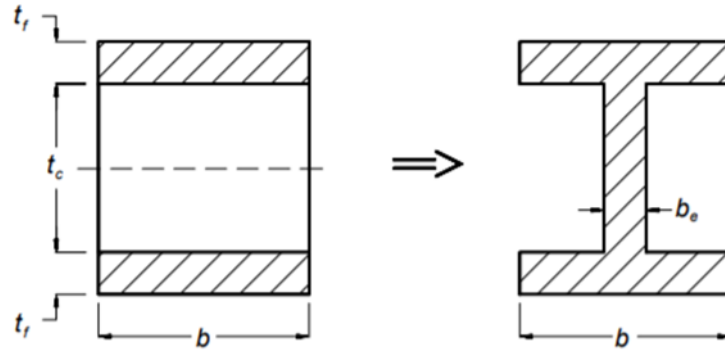


Figure 23: Sandwich structure and equivalent web width of I-beam [44].

In order for the two sections to have the same bending stiffness, the thickness of the web in the I-beam can be calculated by the following equation:

$$\frac{E_c t_c^3 b}{12} = \frac{E_f b_e t_c^3}{12} \rightarrow b_e = \frac{E_c}{E_f} \cdot b \quad (2.10)$$

In this way, a fictional moment of inertia can be calculated as:

$$I = 2 \frac{t_f^3}{12} + 2t_f \frac{d}{2} + \frac{E_c}{E_f} \frac{t_c^3}{12} \quad (2.11)$$

Nevertheless, it is important to note that this I value is only valid for a certain E_f , so that $E_f \cdot I = D$ equation is valid. Care should be taken before using a property such as the moment of inertia as it is considered not well defined unless it is specifically supplied with a modulus of elasticity [44].

2.3 General View of Additive Manufacturing Tehniques

Within the scope of this thesis, it is aimed to give information about the design and production of auxetic structures. In the majority of studies, advanced and rapid manufacturing techniques have been used instead of traditional manufacturing methods since auxetic structures show a porous and hierarchical order. As the results of these studies are based on additive manufacturing methods, information about the definition of additive manufacturing, usage areas, positive and negative aspects and manufacturing techniques will be given in this section.

2.3.1 Principles and methods of 3D printing

Additive manufacturing (AM) is the technique of producing three-dimensional objects from a digital model by layer upon layer. This industry has gained significant value in recent years with its markets such as prototyping, mold making, direct manufacturing, maintenance and repair. Additive Manufacturing, also called AM (additive manufacturing) or 3D printing, has come up with great impact to change classical manufacturing methods. Firstly, it was used for rapid prototyping, but now it is aimed to use finalized products. The reason why AM became hot topic is that to overcome the complex geometry creation. Because, it gives possibility to enhance design freedom almost in every areas.

In AM, the designed 3D geometry is transformed into a series of direction codes followed by a machine to produce the part layer by layer. This capability allows AM to be superior and economical in scope compared to traditional manufacturing technologies [46]. A single AM machine can produce almost any geometry while doing this economically at low volumes.

Machining can have scrap rates as high as 80-90%, this makes AM as a first choice that expensive material used fields like aerospace and defence industries [46]. In addition, component designs can be optimized to take advantage of advanced non-solid filler structures that can only be achieved using an AM process. Non-solid fillings allow a variety of components to be lightweight, which can be invaluable for some industries such as aviation where the weight is incredibly expensive.

Molding and casting processes are used extensively in the industry. However, it takes much more time, and in some cases great investments. Tooling cost is generally the largest percentage of the unit cost in a molded part. As a result, minimum order quantities, often in excess of a thousand pieces, are required to make most applications financially possible. In addition, parts can be produced to order immediately, as AM does not require molds. Therefore, using AM to produce products can result in shorter lead times than a process using injection molding, although cycle times in injection molding are much shorter than AM.

Additive manufacturing method covers many unique processes with different characteristics. It was categorized by the researchers in 2010 and then standardized into seven categories as seen in Table 1 [47].

Table 1: Additive manufacturing processes [47].

Process	Example Companies	Materials	Market
Vat Photopolymerization	3D Systems (US), Envisiontec (Germany)	Photopolymers	Prototyping
Material Jetting	Objet (Israel), 3D Systems (US), SolidScape (US)	Polymers, Waxes	Prototyping, Casting Patterns
Binder Jetting	3D Systems (US), ExOne (US), Voxeljet (Germany)	Polymers, Metals, Foundry Sand	Prototyping, Casting Molds, Direct Part
Material Extrusion	Stratasys (US), Bits from Bytes, RepRap	Polymers	Prototyping
Powder Bed Fusion	EOS (Germany), 3D Systems (US), Arcam (Sweden)	Polymers, Metals	Prototyping, Direct Part
Sheet Lamination	Fabrisonic (US), Mcor (Ireland)	Paper, Metals	Prototyping, Direct Part
Directed Energy Deposition	Optomec (US), POM (US)	Metals	Repair, Direct Part

Each of the processes mentioned in the Table 1 has strengths and weaknesses according to the following items.

- Material that can be used in the process
- Part production speed
- Dimensional accuracy and surface quality
- Material properties of the produced part
- Equipment and material cost
- Accessibility and security depending on the complexity of the process

Due to these different features of the methods, the effectiveness of each process differs from the market.

The 3D printing process begins with the creation of a digital model of the desired object; this is done with some kind of computer-aided design (CAD) software that gives the user precise control to meet the requirements for the desired object. To send the designed part to a 3D printer, the CAD file is converted into an industry standard format (i.e. an STL format). STL is an acronym taken from the term Stereolithographic created by Charles Hull [48]. An STL file type is based on the geometry of triangular shapes [49]. Since all 3D printers print material layers one layer at a time, STL files must also be separated into these layers before they can be sent to the printer; this process is known as slicing and can take a long time for complex files. When the sliced file (i.e. G-code file) is processed, a file is created with the printer's instructions on how best to configure the part. A G-code file stands for G-programming language, a numerical control programming language used to control automatic machine tools. [50].

The structures of the printed objects can include features with protrusions or areas extending away from the part body. Support structures are used to prevent any distortion during process. The building system supports changes or becomes more specific depending on the AM process type. According to study of Lischke, it was suggested that design methods change before sending a part to a 3D printer so that the part is self-supporting and does not require support structures [51]. Based on the geometry, the support structure is determined by the G code algorithm [50]. Figure 24 shows the illustration of CAD geometry input for the 3D printing device.

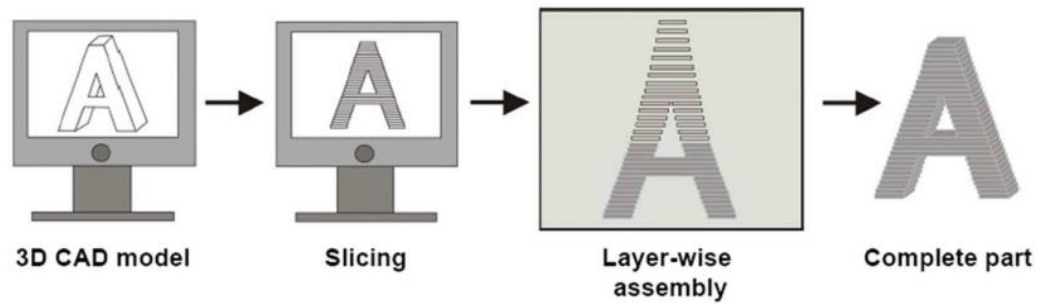


Figure 24: Digital process of additive manufacturing [Anonym].

Although additive manufacturing is based on the principle of fabricating material layer by layer to form the structure, there are many ways to achieve this. In the technical review of the American Society for Testing and Materials (ASTM), the most common additive manufacturing processes are classified as Vat Photopolymerization, Material Jetting, Adhesive Spraying (Binder Jetting), Material Extrusion, Direct Energy Deposition, Sheet Lamination and Powder Bed Fusion [52]. Liquid materials are used as raw materials in Vat photopolymerization. The liquid raw material is combined layer by layer using a kind of Ultraviolet (UV) light source until it is produced in the desired geometry in a vessel reservoir. In Material Spraying, the material is sprayed or deposited as a droplet directly onto the constructed plane. In Binder Spraying, a liquid binder is used to bind the material used in printing and is based on an inkjet head which sprays droplets, the powder binds the substrate together and leaves unused powder behind. The advantages of material jetting are speed, high resolution printing potential, availability of many available materials, and low cost. Material extrusion is a process that melts materials and extrudes them into the building layer. Material extrusion is the most widely known additive manufacturing process. In Direct Energy Deposition, it uses an energy source such as a laser or electron beam to combine materials into layers. Sheet lamination involves collecting of materials such as thin sheets or polymers that are then formed by a 3D printer. In Powder Bed Fusion, fine powder layers of material combined with some form of thermal energy such as laser are used to create the object layer by layer [52]. Some AM techniques are discussed and reviews in upcoming subjects.

2.3.1.1 Laser beam melting (LBM)

In this method, firstly, the powder material is applied on the platform as a layer. Thanks to a cylinder moving on the platform, the powder is distributed on the platform in a

regular and equal thickness. The laser beam travels by melting the powder material to form a thin layer at the bottom of the CAD model, and the first layer is produced by melting. The platform level is reduced by 20-100 micrometers, the surface is covered with a new powder layer, the powder is distributed with the cylinder, and the laser beam travels to form an upper thin layer and adds another layer to the geometry. By repeating the process in this way, layers are produced by melting with the laser beam of the desired geometry. Figure 25 represents the laser beam melting process [53].

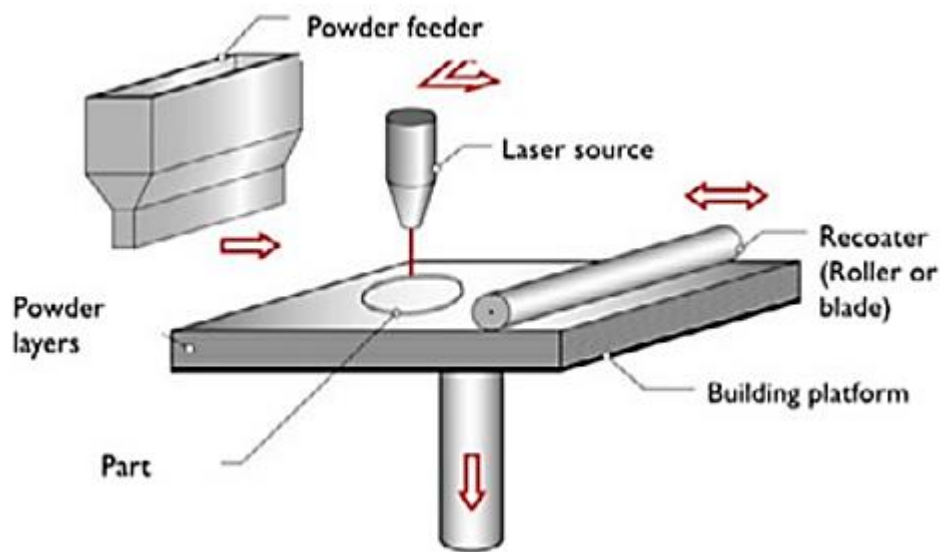


Figure 25: Laser beam melting process [53].

2.3.1.2 Electron beam melting (EBM)

The energy required for melting is provided by the high energy electron beam. The electron beam is controlled extremely precisely and quickly by electromagnetic coils. This process takes place in a low vacuum environment such as 10^{-5} mbar and at high temperature. In each layer production, the temperature of all the dust in the environment is brought to a suitable value and kept at this temperature during the process. This allows it to produce a part that is free from internal residual stress and martensitic structure.

2.3.1.3 Fused deposition modelling (FDM)

In the FDM method, 3D printers enable the production of parts by extruding the molten material usually a kind of thermoplastic flow in overlapping layers boiling together from a nozzle or hole [54]. These types of printers range from industrial size to pen

sizes to be used for hobby purposes in homes. In recent years, new materials have also started to be used in these printers in order to produce parts suitable for use in different fields due to the intense interest. As the most known examples of these; Poly Ether Ether Ketone (PEEK), High Impact Polystyrene (HIPS), Acrylonitrile Styrene Acetate, Poly Ethylene Terephthalate, Poly Carbonate and Poly Amide can be given. Thanks to this production method, structures, which are very difficult and troublesome to produce, especially by normal methods, can be produced at once without the need for additional processing. Especially, the auxetic structures, which are the subject of this thesis, have gained a more prominent place with the development of this technology and have become the subject of intensive studies. An FDM printer with the most basic principle is shown in Figure 26 and schematically below.

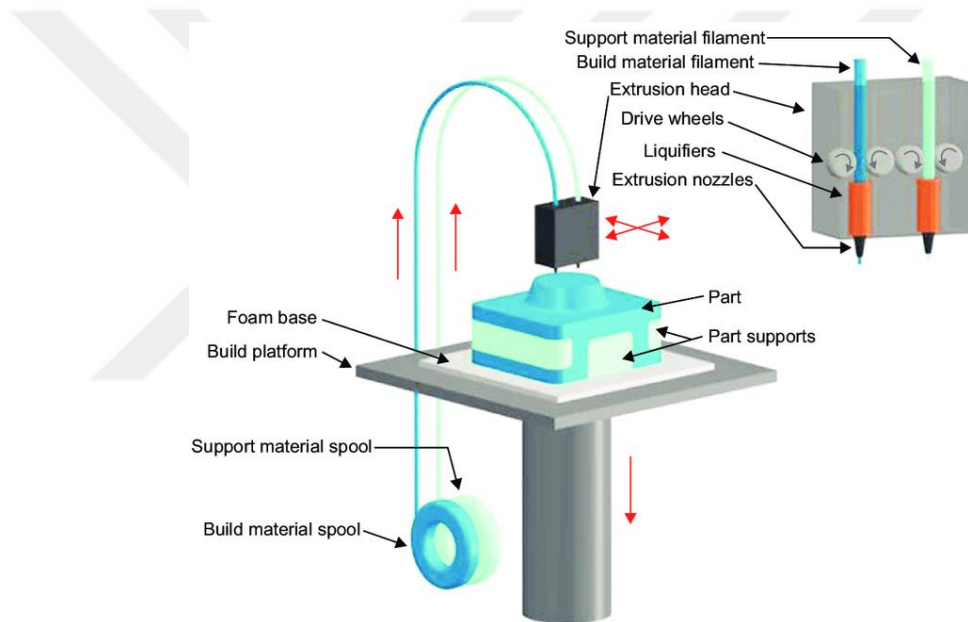


Figure 26: Representation of 3D printer working with FDM principle [53].

2.3.1.4 Direct energy deposition

In the Direct Energy Deposition technique, the material powders that will form the part are poured into the path of the laser beam with the help of a channel, and the laser that will pass through that path immediately melts the material. The material solidifies and forms a layer. Although this method provides fast production, it is not successful in producing lattice structure and inner channel structures. The principle of Direct Energy Deposition method is illustrated in Figure 27.

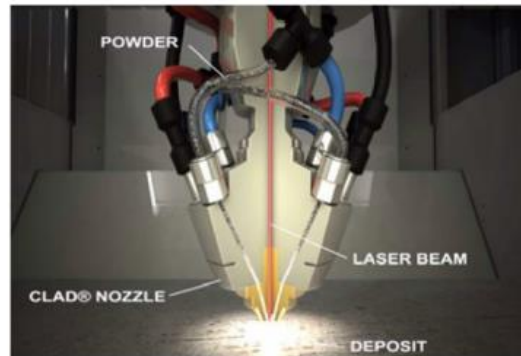
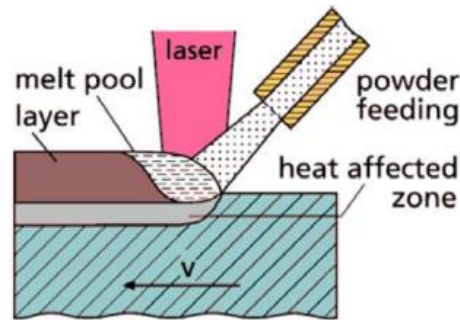


Figure 27: The Principle of Direct Energy Deposition [53].

2.4 Advantages of Additive Manufacturing

Some of the advantages of AM technology can be categorized as listed below:

Mold design avoidance: Since a single piece or multiple parts can be produced by the layered production method, the cost of molds in traditional methods is saved. Although not for large mass production, it is preferred in applications where the cost per piece remains low compared to traditional methods.

Innovative: Many factors that restrict traditional products are eliminated when additive manufacturing is used, and more innovative and original designs can be created. These innovative designs can be for parts that have not been produced before or have not been produced before due to constraints, or they can be edited to improve the properties of an existing and widely used part and bring new features.

Energy saver: Additive manufacturing minimizes the preparatory stages required in many production techniques and also reduces the energy use occurring in these stages.

Environment friendly: In most of the traditional production techniques, production starts with the roughest form of the material, which is called a bar, and goes through many processes until the actual production stage. A certain amount of residual product

is generated in each of these process steps, creating an environmentally polluting element. Even if the material to be processed is ready, the amount of material thrown as sawdust in some parts produced by machining can reach 80% -90% of the main material. With additive manufacturing, products are now reduced to 10% or less. The results of using casting and AM technology comparison in terms of material input energy consumption listed in Table 2.

Table 2: The amount of material and energy during casting and AM techniques [55].

Manufacturing Pathway	Gravity Die Casting – Al	Selective Laser Melting – Al	Selective Laser Melting – SS 316L
Material Input (lb)	4.4	0.7	2.0
Final Part mass (lb)	2.3	0.5	1.3
Life Cycle Stage			
Raw Materials (kBtu)	305	64	68
Manufacture (kBtu)	5	28	87
Transportation (kBtu)	45	7	15
Use Phase (kBtu)	324	73	209
End of Life (kBtu)	1	0	0
Total (kBtu)	681	173	379

2.4.1 Comparison of AM and traditional methods

Some of the better properties of AM technology is listed below.

Small scale production: Additive manufacturing techniques and materials are generally more expensive than traditional manufacturing techniques. Therefore, the production chain must be developed for large scale productions. However, in case of one or more parts, it is preferred because of its flexibility that can achieve quick changes in the part to be produced.

High value products: Although the method does not provide an advantage in low cost products based on mass production due to the slowness of the method, performance and quality are increasingly important in the production of desired parts. In addition to high engineering applications such as the aviation and space industry, it is also preferred in the production of expensive goods and accessories such as jewelry.

Highly complex products: Complex shapes and geometric features are difficult, if not impossible, to produce using traditional methods. Additive manufacturing shows

its importance, especially when it comes to high complexity. This is because modeling a highly complex part in a computer environment does not cause any additional cost and the complex part modeled is easily produced with the dimensions and details specified.

2.5 Application Areas of AM

In line with the increasing demand for additive manufacturing, studies in this field have spread to many areas. With each passing day, more and more companies are realizing the advantages of additive manufacturing and focus on this area. Additive manufacturing can be seen in all areas of life when it takes part in the production phase of the part. The areas where it is used extensively can be seen in Figure 28 [56].

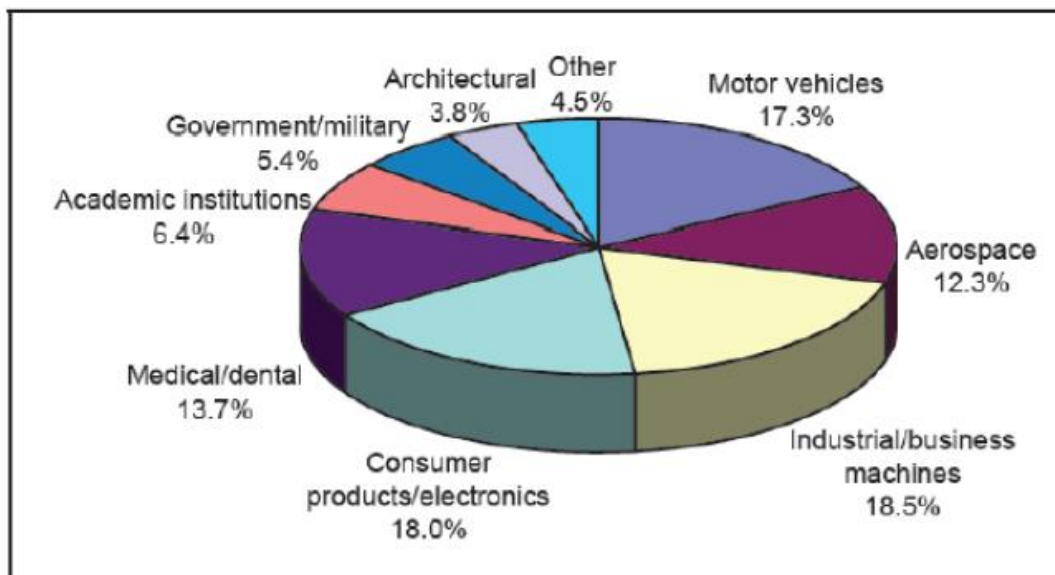


Figure 28: The usage areas of AM with respect to the most common sectors [56].

Although better structural features and efficiency were at the forefront in the early years of additive manufacturing, its use has increased by spreading to different areas with the new ideas put forward in recent years. Issues such as obtaining lighter structures, medical sector applications, creating alternative structures in electronics and energy storage can be cited as examples.

2.6 Materials Used in AM

Almost all kinds of materials can be used with additive manufacturing systems. Polymeric materials are very common in cheap areas and applications that durability

is not important. Thanks to their low melting or glass transition temperatures, they become easily convertible into products. In addition, polymer materials are materials that are widely used in important applications because their properties such as insulating and lightness create advantages over metals. The materials used in additive manufacturing can be summarized as seen in Figure 29.

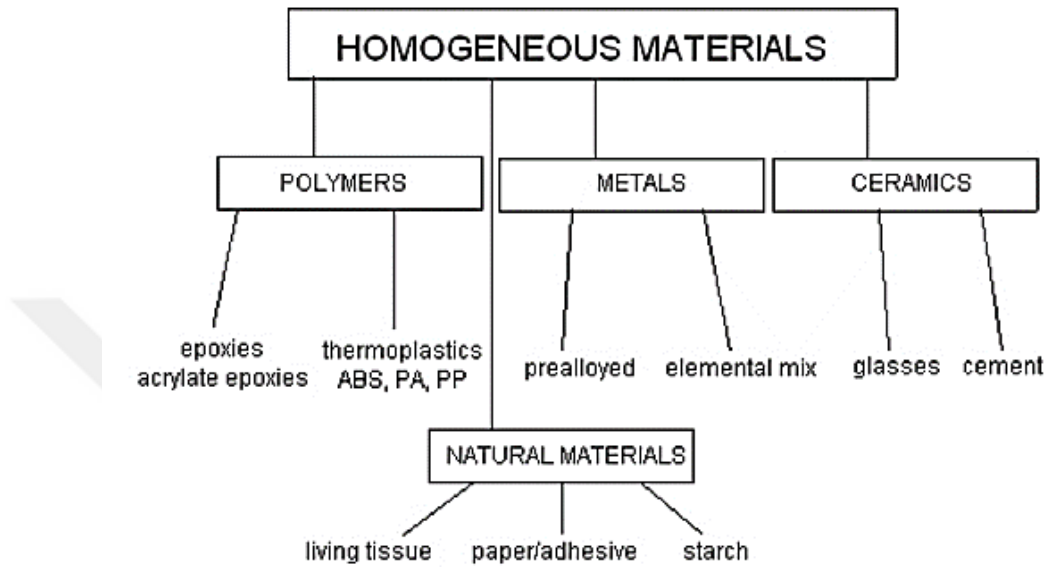


Figure 29: Material classifications used in AM [56].

Durability, high stiffness, high absorption characteristics are the properties that come with the auxetic structures. The material selection is also crucial to improve mechanical properties of the structure. Metallic materials are more expensive than polymeric materials; however, the mechanical properties make metallic materials the first choice between other materials. The metal powders formed by solidification are collected by reaching the collection chamber through the way in the bottom of the chamber where the separation process is located. Although a similar process can be done using water instead of gas, metal powders created with water are fixed to an irregular shape. In the production with gas, the powders have a spherical shape and it provides a great advantage as it allows the powders to flow easily over each other. In addition, the gas separation method is widely preferred because powders of approximately the same diameter can be obtained and many metals can be converted into metal powder by this method.

2.6.1 Metallic materials

Metallic materials are the most commonly used materials in engineering. They are preferred because of their high strength and many other features. Metal powders are used to obtain metal products with AM. When metals that require high energy to be melted or shaped are brought in powder form, processing and handling becomes very easy. The quality of metal powders is an important issue and directly affects the mechanical properties of the part to be produced. Thanks to metal powders, a wide variety of alloys can be included in additive manufacturing technology. Most used alloys are:

- Steels,
- Nickel and cobalt based superalloys,
- Titanium alloys,
- Aluminum alloys,

Apart from these metals, many metal materials are in the process of being evaluated and used for additive manufacturing. The most important examples of these are:

- Copper alloys,
- Magnesium alloys,
- Precious metals such as gold, silver, platinum,
- Metals that cannot be easily machined such as molybdenum, tungsten, tungsten carbide,
- Metal matrix composites.

3. DESIGN PARAMETERS OF METAMATERIALS AND NOVEL AUXETIC STRUCTURE

It is aimed to design a novel auxetic structure within the scope of this thesis. Considering the studies in the literature, many re-entrant structures were first examined, and then the mechanical properties of chiral auxetic structures inspired the novel design. Before the novel design was created, many ancient architectural structures were examined, at the same time, it was aimed to be inspired by the structures in the nature. However, due to the time constraints and the difficulty of finding an original design, it has been set out from the studies in the literature again. One of the most important issues in the design of the original auxetic structure that has been studied is that it provides the NPR. Many design attempts have been made, but NPR has not been observed in both tension and compression simulations.

In addition to these, the original unit cell design was studied first. When the compression and tensile results of various unit cells showed NPR property, these unit cells were reproduced in various directions as they were intended to be used in sandwich structures. The biggest problem encountered is that the replicated structures lose their NPR property.

At the end of all these trials, it was achieved to combine the re-entrant and chiral structures in a unit cell. This structure has shown NPR feature both in the unit cell and in the multiplied sandwich structure. Within the scope of the thesis, unit cell design will be mentioned. In addition, the multiplied sandwich structure will be shown respectively. In addition, one of the changes that can be optimized in the design is shown and what else is mechanically interchangeable is also discussed.

Before mentioning the original design in the thesis, the design parameters of the auxetic unit cells will be mentioned. As an example, the design of re-entrant, double arrowed, and tetra-chiral auxetic structures will be mentioned. However, before deep diving into design parameters brief literature review is shared.

3.1 Literature Review

Especially in the last 30 years, there are many studies on sandwich structures and core geometries. Important researches in which significant developments and advances

have been made regarding the study subject are briefly given here. In particular, design solutions, numerical analyzes and test results studied on auxetic structures, which are the source of this study, are shared in this section.

Lakes, firstly discovered the negative Poisson's ratio effect in polyurethane foams with a re-entrant structure [18]. Later then with new studies, names such as anti-rubber, auxetic and dilatational structure were given by researchers. Later Lakes presented a review of auxetic materials, production methods, the results of these unusual physical properties, and developments after the discovery of their research [57].

Thanks to biomechanical benefits of auxetic structure properties, antitetra-chiral and antichiral-reentrant structures are developed by researchers to take an advantage to build clinical stent applications [58,59].

The superior properties of auxetics are obtained by changing the geometrical parameter; such as length of ligaments, angle, and cross section area. Also, the material properties of these structures play a vital role to determine the mechanical properties. Each auxetic structure can be developed for a certain purpose; it could be a vibration damping, energy absorbing, and noise cancellation. Each of these purposes can be obtained by changing the topology of the unit cell of the structure. Changing topological parameters of the unit cell will push the limits of conventional manufacturing methods. Therefore, the developing additive manufacturing techniques enable design freedom to researchers. Some studies carried out different auxetic structure geometries classified as woven, foam, and lattice structure [60-62]. Wang et al. studied the interlocking mechanism of 3D periodic additive manufactured auxetic part [63]. Yuan et al. introduced selective laser sintering manufacturing method for the fabrication of flexible 3D auxetic metamaterial [64]. According to study of Hou et al. auxetic and non-auxetic sandwich structures impact resistance was analyzed by tests [65]. As a result of three-point bending tests re-entrant auxetic core structure shows better results in terms of resistance under cyclic impact loads. Liu et al. investigated the behavior of the re-entrant auxetic honeycomb structure under impact load by simulating the in-plane dynamic loading using FEM and compared the energy absorption performances of re-entrant honeycombs and hexagonal honeycombs [66]. They found that when subjected to compression stresses of the same magnitude, the re-entrant honeycomb structure can absorb more energy through plastic deformation. However, they add that if the maximum stress is the primary important point for the

material, the re-entrant structure tends to generate higher stress to dissipate the same amount of impact energy.

The main subject of the study conducted by Imbalzano et al. consists of sandwich panels with auxetic lattice cores restricted between metallic surfaces for localized impact resistance applications [67]. In this study, the performances of the structures under localized effect were analyzed numerically, taking into account the effects related to speed. As a result of the study, it was found that composite panels with auxetic core can absorb a similar amount of energy through plastic deformation, while the maximum back face displacements were reduced by up to 56% due to local densification and plastic deformation of the auxetic core. Yang et al. studied the mechanical properties of different structures theoretically, computationally and experimentally for the potential applications of body protective pads for armor purposes [68]. Among these structures, which they produced using different materials, there are hexagonal honeycomb as well as re-entrant and double arrowhead auxetic structures. The results of the study reveal that auxetic structures can be effective in reducing shock forces and each structure and material combination exhibits unique structural properties such as stiffness, Poisson's ratio and shock load damping efficiency. They also clearly stated that, especially, the auxetic structures had better shock load absorption performance than non-auxetic structures.

Energy absorption capabilities of lattice structures can be enhanced by changing lattice core unit cell geometry. The wall length, wall thickness, and angle is important to shape mechanical properties. In lattice structures, it is known that honeycomb lattices occupy great percentage in the researches. By the modification of honeycomb structures, auxetic re-entrant shapes can be obtained by changing the angle parameter of honeycomb unit cell. In the research that is done by Zhou et al. re-entrant auxetic structure in-plane compression properties were investigated [69]. Miller et al. analyzed the planar compression behavior of Tetrachiral and Hexachiral combs using analytical and Finite Element simulations with both explicit and implicit formulations [70]. Chiral honeycombs have been shown to have specific bending loads of greater density and are therefore best suited for use in applications where maximum bending strength is required, but this behavior is sensitive to relative internal geometry. In addition, the visco-elastic performances of the materials improve in the presence of auxetic behavior. Some studies have proven that the modulus of two-phase composite foams

increases when using re-entrant honeycomb structures. In addition, in this study, the possibility of improving both stiffness and modal loss factors was demonstrated by Scarpa et al. by using auxetic honeycombs [71].

Within the context of this thesis study, novel auxetic design literatures are also investigated to find the appropriate innovative structure, and gain an inspiration. One of the novel design study was carried out by Li et al. [72]. In this study, in-plane large deformation results were studied by using analytical methods, FEA and test validation by experimental results. Khare et al. developed novel s-hinged auxetic unit cell which can be manufactured by 3D printing technology to investigate fatigue behaviour and assembly [73]. In this study mechanical properties were determined by parametric analytical model. Additionally, this study underlined the bi-stable geometries that can be evolved by any changings in geometry, as AM technology enables all of the topological changes.

Another research according to enhancement of in-plane impact energy absorption was investigated by Wang et al. [74]. In this study, especially cell wall thickness effects were discussed to evaluate mechanical properties. Some studies are carried out by creating auxetic designs by inspiring from architecture and nature. Rafsanjani and Pasini studied on the bistable auxetic structure which is the inspiration of ancient geometric motifs [75]. The mechanical performance of the auxetic structure were assessed by mechanical testing and FEM. This study shows that nature and history could help to create novel and superior structures. Inspried ancient motifs are illustrated in the Figure 30.

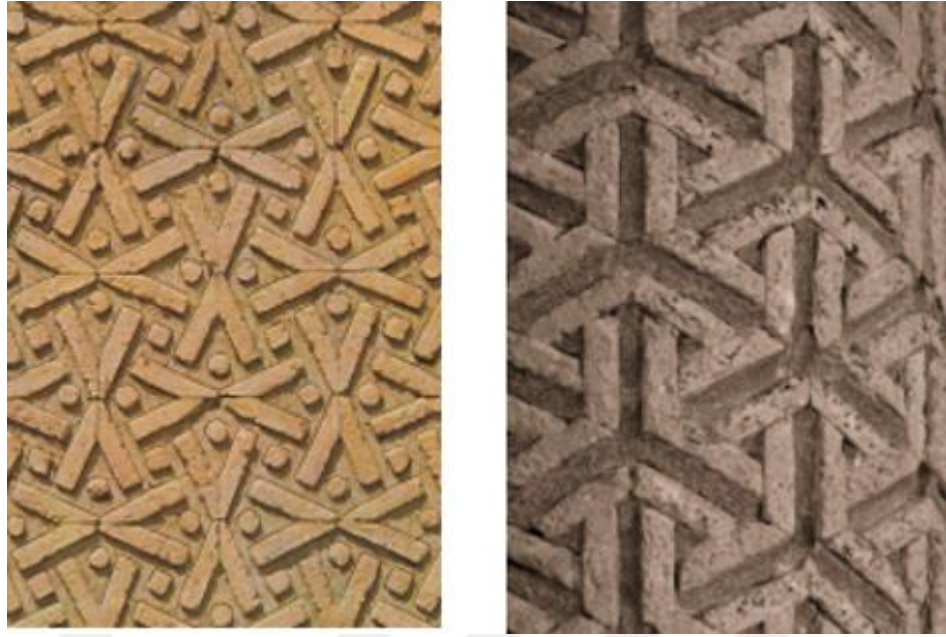


Figure 30: Square and triangular motifs in the Kharraqan twin tomb towers in western Iran [75].

It is not an obligation to build novel structure just creating new geometry that is not done before. Some studies dwell on changing minor parameters on geometries that are commonly used. Meena and Singamneni are studied filleting of sharp corners of auxetic structure [76]. After filleting NPR varies from -1.5 to -1.65 values. Also after finding optimum fillet radius, stress concentration points moved to the locations that are not critical. Su et al. developed a novel auxetic structure with supporting beams [77]. These beams enhance the stiffness of the structure by mitigating buckling result. This study is also another design flexibility for creating novel structure. Among the all auxetic structures the most used designs are re-entrant, chiral, and rotating-structures. However, some studies showed that new geometries that have not done before can be established in the literature. One of the example study was carried out by Meena and Singamneni [78]. In this study, re-entrant shape is an inspiration for creating S shaped auxetic structure. Besides typical auxetic structure, developed structure shows better deformation characteristics when compared to re-entrant auxetics, surprisingly. They also pointed out that re-entrant auxetics suffer from row-wise collapsing, while S-shaped unit cell shares the displacement across the whole structure assembly. The comparison between typical re-entrant auxetic and S-shaped unit cells are illustrated in Figure 31.

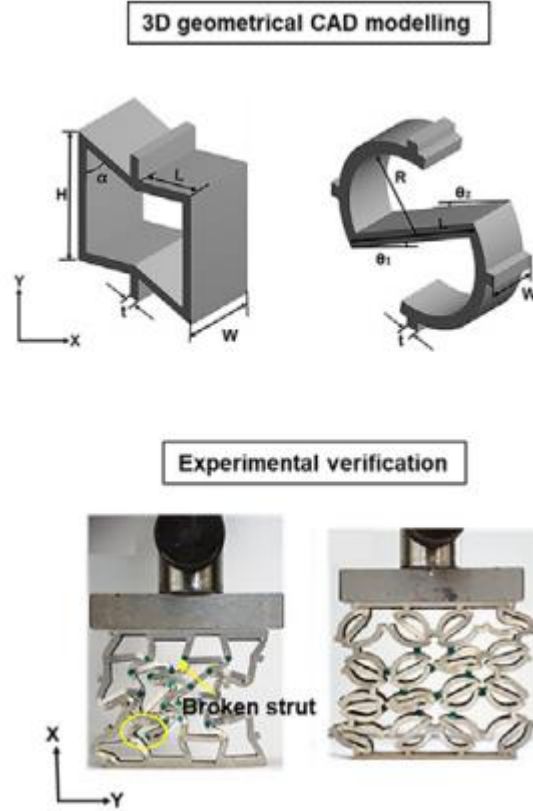


Figure 31: Comparison between re-entrant and S-shaped unit cells and their deformations [78].

Not only re-entrant structures but also chiral structures are take place in the most of the design studies. It is difficult to create a novel structure that has better mechanical properties when compared to previous studies. Hierarchical patterns are well known among the sandwich core structures. This is also being an inspiration for building novel auxetic structure. Jiang and Li created hierarchical auxetic structure that are consist of re-entrant and chiral structure shapes [79]. Combining re-entrant angle property and chirality has well response in terms of large deformations. This new design has potential using in smart materials, deployable structures, and shape memory applications. Research was done by doing FEA simulations and mechanical experiments. The novel combination design is showed in Figure 32.

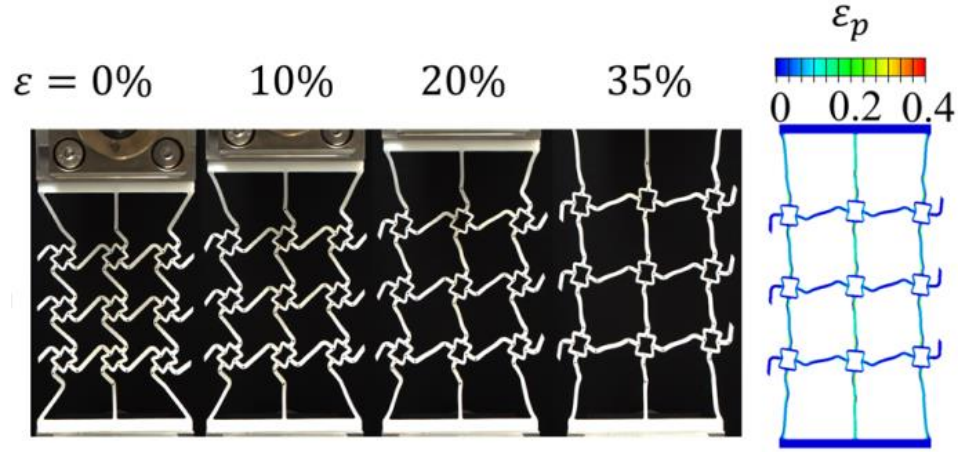


Figure 32: Re-entrant and chiral combination of novel auxetic mechanical test and FEA simulation [79].

With the development of production methods, design diversity is increasing at the same rate. The freedom provided in design has enabled researchers and engineers to provide multi-functionality to the structures. The use of mechanically autonomous systems is also possible with new designs. In recent years the attention on the studies about smart materials, shape memory alloys and deployable structures has increased. Autonomous deployable structures in space research, aviation and defense industry will be included in more literature day by day. The programmable autonomous deployable structure developed by Wagner et al. is an example of this [80]. In this study, the structure is also in the form of re-entrant auxetic. The main purpose is to provide shape change according to the type of mechanical loads that the structure is exposed to. This provided an advantage in terms of weight by preventing the addition of extra parts in the whole structure.

3.2 Auxetic Metamaterials Design Parameters

It is aimed to design a novel auxetic structure within the scope of this thesis. Considering the studies in the literature, many re-entrant structures were first examined, and then the mechanical properties of chiral auxetic structures inspired the novel design.

Before the novel design was created, many ancient architectural structures were examined, at the same time, it was aimed to be inspired by the structures in the nature. However, due to the time constraints and the difficulty of finding an original design, it has been set out from the studies in the literature again. One of the most important

issues in the design of the original auxetic structure that has been studied is that it provides the Negative Poisson's Ratio (NPR). Many design attempts have been made, but NPR has not been observed in both tension and compression simulations.

In addition to these, the original unit cell design was studied first. When the compression and tensile results of various unit cells showed NPR property, these unit cells were reproduced in various directions as they were intended to be used in sandwich structures. The biggest problem encountered is that the replicated structures lose their NPR property.

At the end of all these trials, it was achieved to combine the re-entrant and chiral structures in a unit cell. This structure has shown NPR feature both in the unit cell and in the multiplied sandwich structure. Within the scope of the thesis, unit cell design will be mentioned. In addition, the multiplied sandwich structure will be shown respectively. In addition, one of the changes that can be optimized in the design is shown and what else is mechanically interchangeable is also discussed.

Before mentioning the original design in the thesis, the design parameters of the auxetic unit cells will be mentioned. As an example, the design of re-entrant, double arrowed, and tetra-chiral auxetic structures will be mentioned.

3.2.1 Design parameters of re-entrant auxetic structures

The use of sandwich panels has an important place in lightening structural applications. In most applications, generally preferred sandwich structures with honeycomb geometry core structure. While these structures work very well especially in planar sandwich panels, when used in the core of curved or cylindrical sandwich structures, they cause local collapse and structure buckling in the core of the structure. For this reason, it was necessary to make the necessary changes in the honeycomb geometry to make it suitable for curved and cylindrical sandwich structures. With various design changes in hexagonal honeycomb geometry, behavior with positive Poisson's ratio can be transformed into a structure with NPR [15]. The structure with this NPR is the re-entrant geometry which is the most known geometry among auxetic structures. While the traditional hexagonal honeycomb geometry has angles of 120° between the inner walls, the re-entrant auxetic structure consists of the hexagonal honeycomb in the form of an arc and the interior angles vary according to the design of the structure. The difference between proper hexagonal honeycomb structure and

re-entrant honeycomb structure is shown in Figure 33 below. The Poisson's ratio of the re-entrant core geometry depends on the angles between the walls of the building and geometric parameters [81].

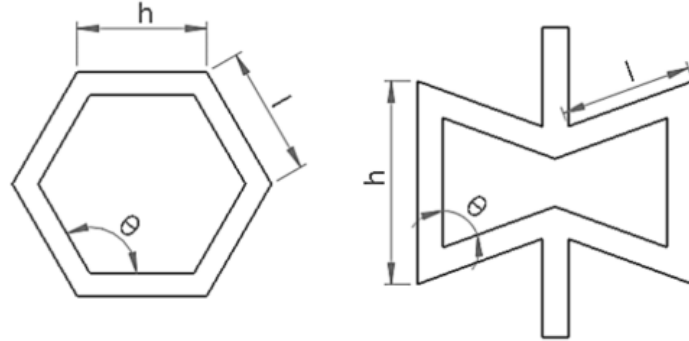


Figure 33: Regular hexagonal honeycomb and re-entrant auxetic geometries [81].

3.2.2 Design parameters of double arrowed head auxetic structures

The double arrowed head auxetic structure discussed in this study was first proposed by Larsen et al. [82], as shown in its two-dimensional form in Figure 34 below. A unit cell structure symmetrical with respect to the vertical axis is shown in Figure 34.b. Here the geometric parameters can be defined as: θ_1 and θ_2 denote the corresponding angles between inclined struts AB and BC and the vertical axis AC, and l , A and B are the horizontal distance between the two vertices. Unless otherwise stated, it would be correct to assume that cell walls are uniform in thickness h (this will differ in functional graded cell geometries).

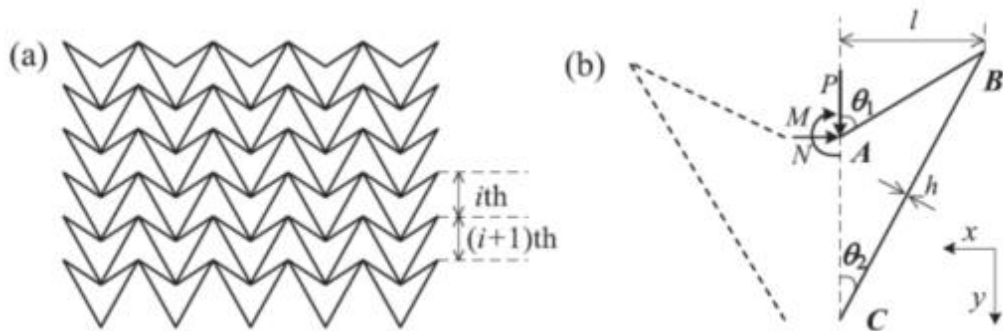


Figure 34: Double Arrowed Head Auxetic structure a) Multiplied Structure b) Unit Cell [82].

3.2.3 Design parameters of tetra-chiral auxetic structures

Chiral honeycomb structures are auxetic cellular materials that show a negative in-plane Poisson's ratio. The theoretical and experimental investigation of these honeycombs was first done by Prall and Lakes [83]. From a mechanical point of view, honeycombs composed of chiral structures were previously described as structures with an in-plane Poisson's ratio of -1 due to symmetry constraints. This type of honeycombs with reduced symmetry may be anisotropic, but rarely can be encountered as special orthotropic. The negative Poisson's ratio gives the chiral structure some unique properties, such as a dome-shaped or synchlastic bending behavior in the out-of-plane direction, in contrast to the saddle-shaped behavior observed in traditional hexagonal honeycomb structures. Chiral honeycombs offer significant advantages over traditional hexagonal honeycombs, compression and shear strength are partially separated between cylinders and bonds. Although there are chiral structures in different geometries, the most known and most commonly used chiral structures are the "hexachiral" and "tetrachiral" structures shown in Figure 35 below.

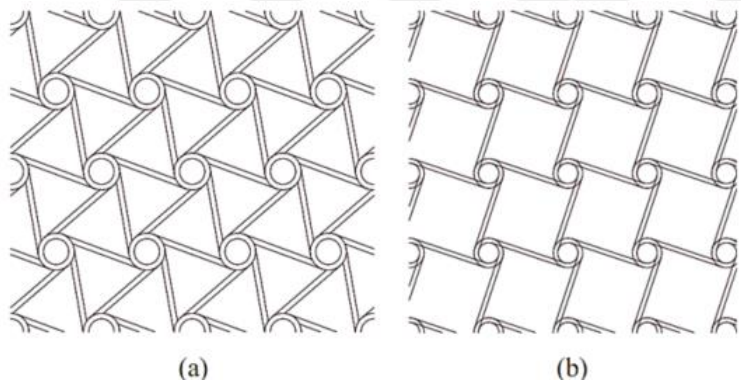


Figure 35: Chiral Structures a) Hexachiral Auxetic b) Tetrachiral Auxetic [84].

Chiral honeycomb structures have been found to have Poisson's ratios in the range $-1 < \nu < 0$ by experimental and numerical examinations. A schematic representation of the tetra-chiral structure undergoing uniaxial tension in the X-direction and free body diagram(FBD) is shown in Figure 36; axial loading(a), FBD of axially loaded tetrachiral (b), shear loading of tetrachiral auxetic(c), FBD of shear loaded tetrachiral (d). A unit cell contains a cylinder (knot) that is supposed to be rigid and four half links.

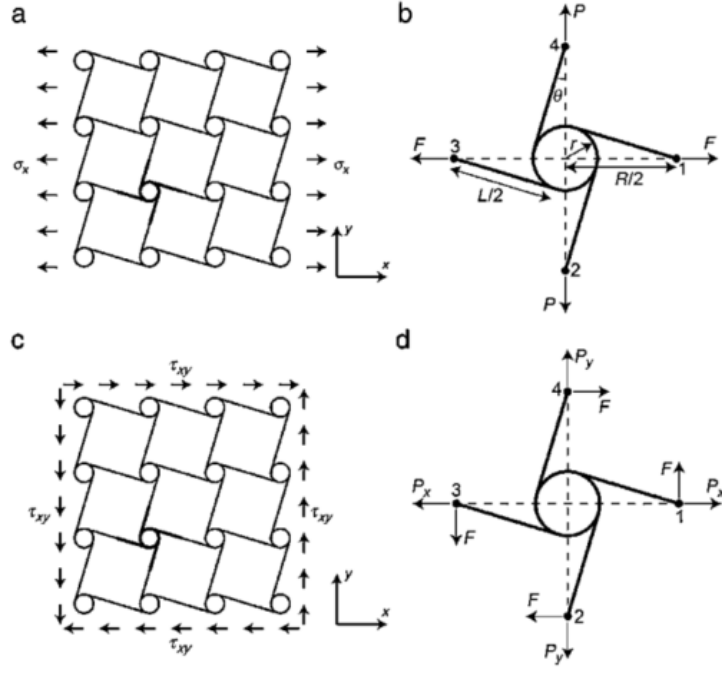


Figure 36: Tetrachiral structure and FBDs [89].

Before passing to the results of the design criteria and numerical analysis, equations expressing the Poisson's ratio, effective modulus and strength under the compressive loads of the auxetic structure are included. Re-entrant auxetic structure, which is widely used for this, has been discussed.

3.3 Mechanics of Re-entrant Auxetic Materials

In this section, the specific mechanics of auxetic metamaterials will be discussed briefly. Re-entrant shaped auxetic structure is selected, as it is the most known and used auxetic structure among the literature.

3.3.1 Poisson's ratio

Under compression load the Poisson's ratio in the Z direction can be easily obtained:

$$\nu_{zx} = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\frac{2\Delta x}{L \sin \theta}}{\frac{\Delta z}{H - L \cos \theta}} = -\frac{2(\alpha - \cos \theta)\Delta x}{\sin \theta (2\Delta z_1 + \Delta z_2)} \quad (3.1)$$

In equation (3.1) α is defined as $\alpha = \frac{H}{L}$. The design parameters of re-entrant auxetic structure is showed in Figure 33 before. According to study Yang et al., the relation of Poisson's ratio between α and θ parameters is shown in Figure 37 under 10 kPa

compression load [85]. The solid material property values used for calculation when creating the graph are taken from Ti - 6Al-4V. It is clearly seemed that the effect of two different parameters on Poisson's ratio. The NPR value is increased while α is increased, and θ is decreased. It can be observed that the Poisson's ratio values, when relatively small, become more sensitive to the re-entrant angle θ ; This is potentially a useful feature during engineering designs.

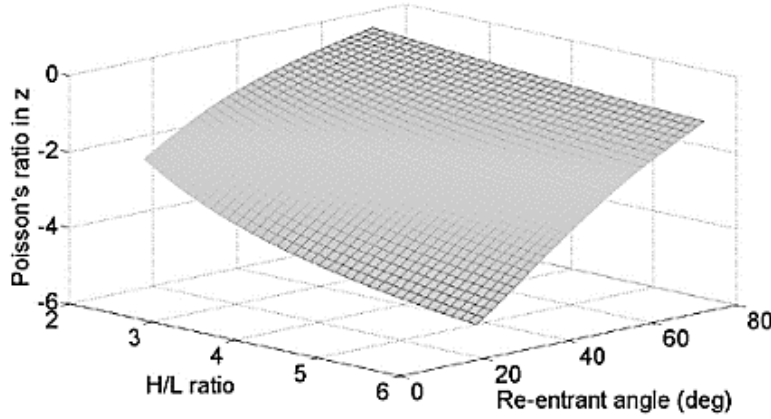


Figure 37: Poisson's ratios under compression with different designs [85].

Effective modulus of re-entrant auxetic structure

During the calculation of the active module, the unit cell structure is considered as a block and the module value can be written for the unit cell as follows:

$$2(H - L \cos \theta) \times 2L \sin \theta \times 2L \sin \theta \quad (3.2)$$

Therefore, the effective modulus is always lower than the modulus of a solid material block with the same overall dimensions. The effective modulus of the re-entrant honeycomb structure can be easily calculated as:

$$E_z = \frac{\sigma}{\epsilon} = \frac{\sigma}{\frac{\Delta z}{H - L \cos \theta}} = \frac{\sigma(H - L \cos \theta)}{(2\Delta z_1 + \Delta z_2)} \quad (3.3)$$

Also total deformation decrease can be calculated as:

$$\Delta z = 2\Delta z_1 + \Delta z_2 \quad (3.4)$$

E_z/E_s is used to evaluate the effect of geometry on the active module. Here, E_z stands for the effective modulus of the auxetic structure in the z direction, while E_s represents

the modulus of the solid material. Figure 38 can be taken to show the effects of design parameters on the effective module E_z .

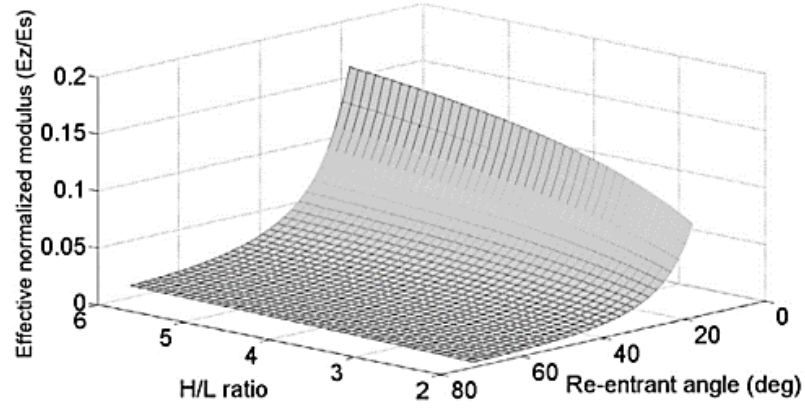


Figure 38: Effective Modulus Change Under Geometric Parameters of Re-entrant Auxetic [85].

It is clearly seemed that effective modules is increased while H/L is increased, and θ angle is decreased.

3.3.2 Compression strength of re-entrant auxetic structure

According to study Yang et al. [86], the Von Mises stress of re-entrant auxetic can be derived as:

$$\sigma_1 = \frac{\sigma}{2} + \sqrt{\frac{\sigma^2}{4} + \tau^2} \quad (3.5)$$

Here σ and τ represent the normal and shear stress on the rod, respectively; σ_1 is the principal stress. The main criterion to be met here should not be forgotten: $\sigma_1 < \sigma_y$ where σ_y is the yield strength of the solid material. The maximum compression force for the structure under compression load is calculated as:

$$\frac{F_z L}{8} \sin \theta = \frac{(\sigma_y^2 - \frac{9F_z^2 \sin^2 \theta}{64t^4})t^3}{4\sigma_y} - \frac{F_z^2 \cos^2 \theta \cdot \sigma_y}{\left(64 \cdot \sigma_y^2 - \frac{9F_z^2 \sin^2 \theta}{t^4}\right)t} \quad (3.6)$$

Then the F_z value can be obtained by solving equation 3.28 numerically. By obtaining this value, the stress value σ_z in the compression direction can be obtained by using the following equation:

$$\sigma_z = \frac{F_z}{2L^2 \sin^2 \theta} \quad (3.7)$$

After these basic formulas and information used in numerical calculations are given, we can move on to the novel auxetic core design used in the thesis. Especially, one of the main reasons for the detailed examination of this structure is the superior combined advantages of the building. This core geometry, which gives the structure a good strength and a very superior energy absorption ability when used as a sandwich core, also has many ergonomic and designable usage advantages with its cavities and pores in the structure.

3.4 Novel Auxetic Structure Design

The design to be created within the scope of this study was first requested to have a negative Poisson's ratio. The unit cell was formed first, respectively, and a three-dimensional plate structure was obtained by mirroring and deriving the formed unit cell with sequential sequencing method. It was stated that the novel three-dimensional structure created showed negative Poisson's ratio. Afterwards, the mechanical properties of the novel auxetic structure was investigated by FEM.

The primary purpose of the novel auxetic structure designed is to contribute to the existing models in the literature with a new design. In addition, the mechanical properties of the created model were tried to be superior by changing design parameters, and the missing or open-to-development aspects were identified in order to inspire future studies.

3.4.1 Unit cell design parameters

While modeling, it was desired that the structure has NPR as well as the properties of the re-entrant and chiral structures that are the source of inspiration. While creating the unit cell, the smallest element that is cannot mirrored was drawn. Then, a unit cell was created by reproducing from the symmetry axes with the help of the CAD program. Unit cell representation is made in Figure 39.

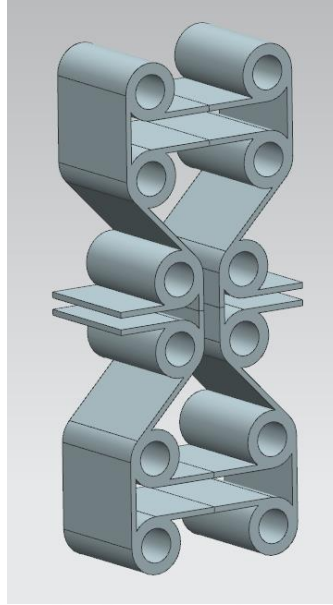


Figure 39: Novel auxetic unit cell design.

When unit cell design is examined, circular cross-section elements are located at the corner nodes of the cell, and besides the circular corners supporting frame shape is similar to the re-entrant structure. It is obvious that this novel design was inspired from the combination of re-entrant and chiral structures. Within the scope of the thesis, the basic parametric geometrical changes are applied on default novel design. The parameters can be listed as: diameter of corner circular cross sections (A&B), thickness of supporting lengths (C), and angle of the inner structures (D). However, mathematical modelling optimization like topology optimization is not studied in this context. It is possible to enhance mechanical characteristics of the structure while decreasing mass properties. The geometric parameters are shown in Figure 40.

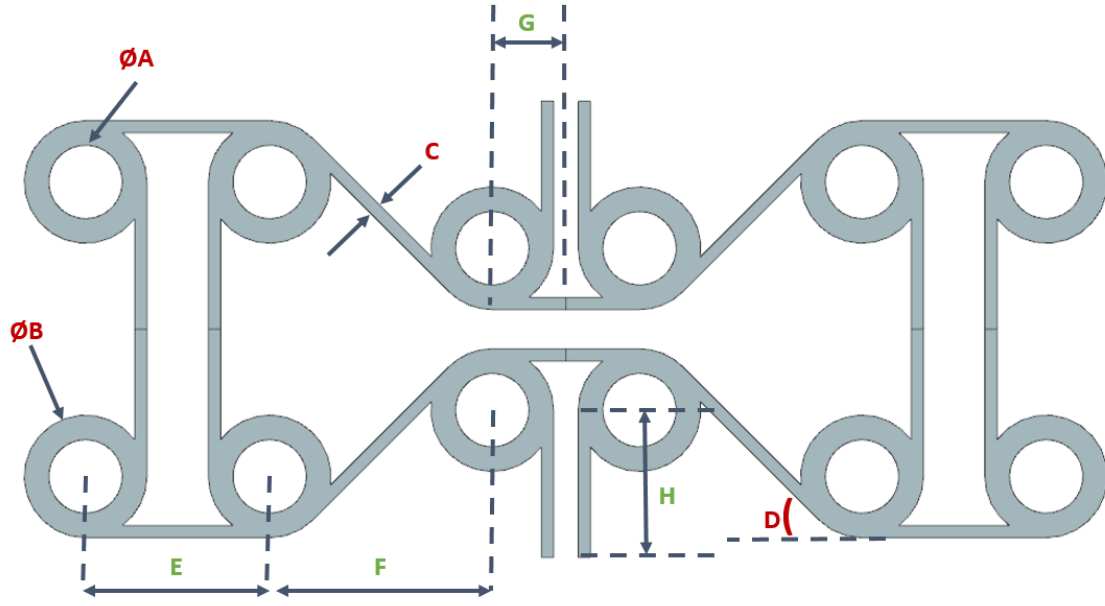


Figure 40: Basic geometric dimensions of novel auxetic design.

In Figure 40 basic geometric dimensions are shown. Red colored dimensions are the parameters to be changed for having an idea how mechanical design respond to any geometrical changes. In Table 3, basic dimensions and parameters are determined.

Table 3: Design parameters information.

Design No.	Variation	A [mm]	B [mm]	C [mm]	D [degree]	E [mm]	F [mm]	G [mm]	H [mm]
1	Default Design	3	5	0.5	45	7.5	9	3	6
2.1	Diameter Parameter	1.5	2.5	0.5	45	7.5	9	3	6
2.2		6	10						
3.1	Thickness Parameter	3	5	0.25	45	7.5	9	3	6
3.2				1					
4.1	Angle Parameter	3	5	0.5	30	7.5	9	3	6
4.2					60				

As can be seen in Table 3, there are 4 different designs that are created by changing three different parameters which are diameter, thickness, and angle. All other design dimensions are hold as same value while preserving geometric integrity of novel the

unit cell. These parameters are for 2D plane dimensions; additional thickness dimension for making design 3D is given as 10 mm for all designs.

3.4.2 Assembly condition of novel structure

In the FE analyses, the tension and compression behavior of the unit cell were primarily examined. In the following titles, it has been shared that the unit cell shows the NPR property under the influence of both compression and tensile displacements. However, the original auxetic design that is planned to be used in real life must be included in the sandwich structure. In this context, the unit cell has been periodically reproduced on two axes and supported by plates that will form the sandwich structure. The replication scheme of the unit cell and the final sandwich structure are shown in Figure 41. All design variations are repeated in sandwich structure form.

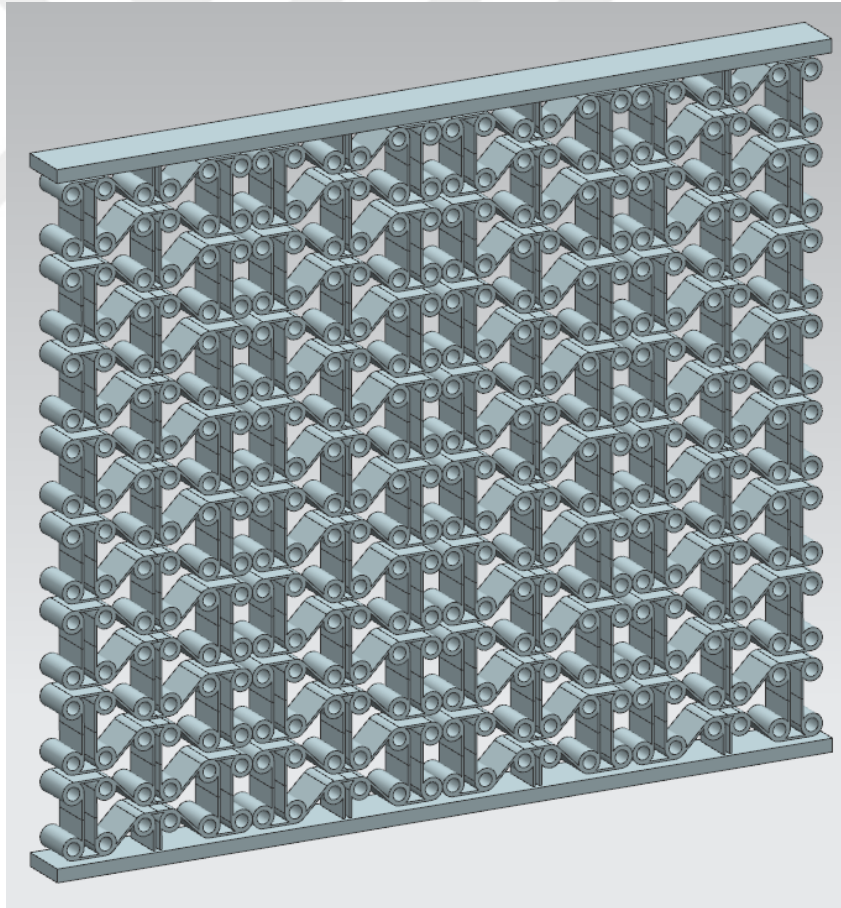


Figure 41: Sandwich novel auxetic structure.

Design freedom provided by AM enables topology optimization in buildings. In this study, topology optimization has not been studied, but the design mass reduction is

shown in Figure 42. This design difference has been achieved by providing holes on the support features of the structure to create a re-entrant hierarchic structure. In this way, both macro and micro scale NPR property has been captured and contributed to the novel design. In Figure 43 finalized sandwich structure for holed geometry is also shared.

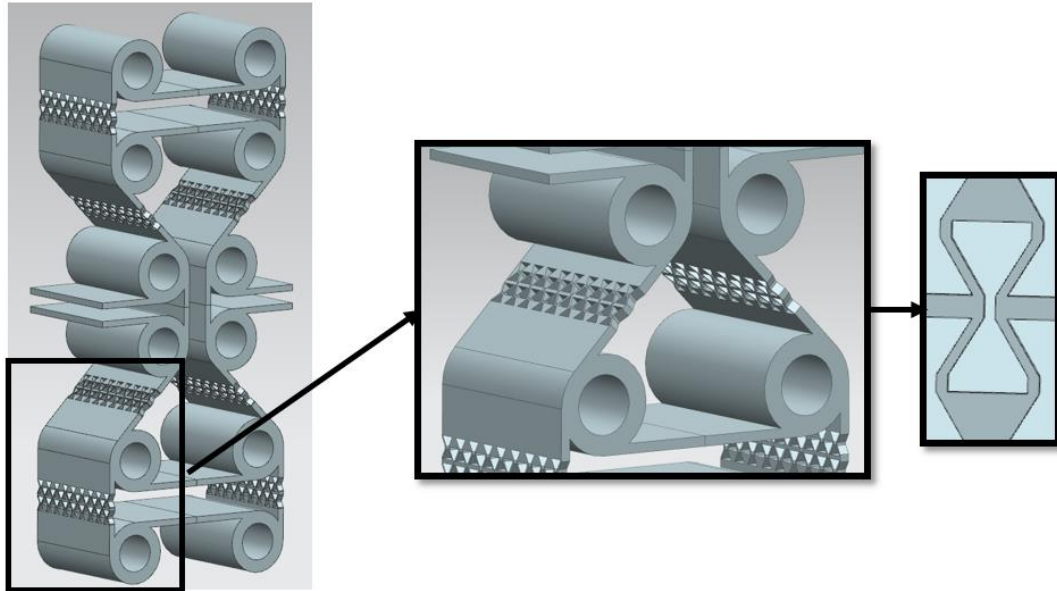


Figure 42: Mass optimized novel auxetic hierarchic structure.

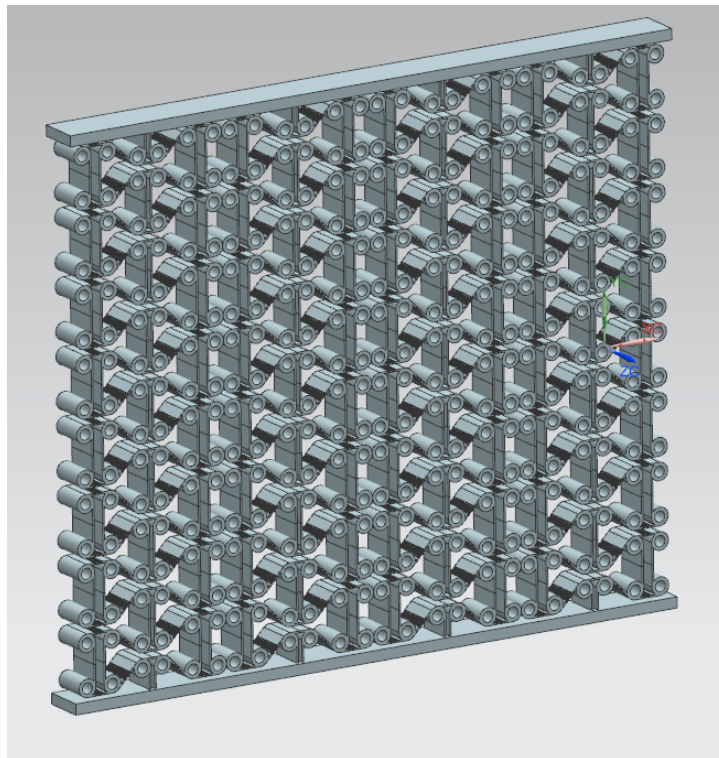


Figure 43: Mass optimized novel auxetic hierarchic sandwich structure.

From the perspective of design, through the innovative unique cell design is achieved using both re-entrant and chiral mechanisms. In terms of sandwich core structure orientation, it is also achieved NPR in the displacement direction. Tensile and compression displacements were applied each geometries and orientations, respectively. Poisson's ratio versus deformation change was also illustrated. Furthermore, different impact velocities were applied from the upper body of default sandwich structures to evaluate deformation mechanisms and stress distributions. FE simulation results are shared through the upcoming subjects.





4. MODELLING, SIMULATION, AND RESULTS

Structural evaluation of the designs has been made by using the FE methods in order to interpret the results of the design changes. It is thought that the smallest detail to be changed in the parameters will have a great effect on the mechanical behavior of the structure. Within the scope of the thesis, an experimental study has not been carried out, but it is aimed to obtain realistic results with simulation technology using the finite element methods.

As a result of the changed parameters, the structures were subjected to displacements in the tensile and compression directions, respectively. As a result of these displacements, the Poisson's ratios of the structures were compared. Then, the reaction forces occurring in the unit cells of the structures were extracted. When comparing reaction forces, calculations were made for unit displacement and unit mass. The reason for this is to determine the stiffness rate per unit mass. Additionally, the impact analyses were carried out for the default design for three different impact velocities. The explicit analysis is done for the impact simulations, as explicit solver method is more usable when large amount of strains are important.

During FE analyses, Ansys 2020 R1 version has been used. For quick response high performance computing (HPC) is used especially for the explicit analyses.

4.1 Definition of Finite Element Model

Finite element model is created by using 3D solid elements. During modelling higher order 3D solid elements (Solid186) are used. These elements have 20 nodes (corner nodes and mid nodes) with 3 degrees of freedom (DOF). Furthermore, in case of contact situation between gaps inside the geometry, surface contact elements (Conta174 & Targe170) are defined for true force distribution. Material is selected as low carbon steel as an input for all FE models. Because, design criteria and results are desired to free from material property effects. The physical and mechanical properties of low carbon steel material is listed in Table 4 [87].

Table 4: Material properties for low carbon steel [87].

Density [kg/m ³]	Young's Modulus	Poisson's Ratio	Yield Strength [MPa] - Tensile	Yield Strength [MPa] - Compressive
7850	200000	0.3	250	250

If the boundary conditions are examined, a displacement that does not exceed 10% of the length of the structure parallel to the direction of displacement is applied. If the boundary conditions are examined, a displacement that does not exceed 10% of the length of the structure parallel to the direction of displacement is applied. In addition, the structure was held fixed from the bottom plate and the same amount of tension and compression (+/- 1.2 mm) was applied respectively. While creating the model mesh, various mesh number and element geometry trials were made. FE analysis runs were taken with these trials. In order to have proper analysis result, the mesh convergence study has been carried out. There are 5 different element size FEM analysis trials to have suitable mesh size. Finally, the most suitable mesh convergence has been caught with 0.4 mm element size with 0.8% mesh convergence rate. According to mesh convergence study Patil and Jeyakarthiskeyan, below 3% difference in FE results mesh quantity values are assumed as acceptable [88]. The average element number is 3,500,000, and node number is 17,000,000. Mesh convergence rates and element size informations are given in Table 5. Additionally, maximum equivalent Von mises comparison for different element size trials showed in Figure 44.

Table 5: Mesh convergence comparisons.

Element Size	Element Number	Node Number	Max. Equivalent Stress	% Difference
3 mm	34,098	216,779	256.2	First Trial
1 mm	142,608	859,882	236	7.9%
0.5 mm	687,039	3,810,256	213.7	9.4%
0.4 mm	1,547,802	7,932,487	222.1	4%
0.3 mm	3,521,185	17,014,327	220.3	0.8%

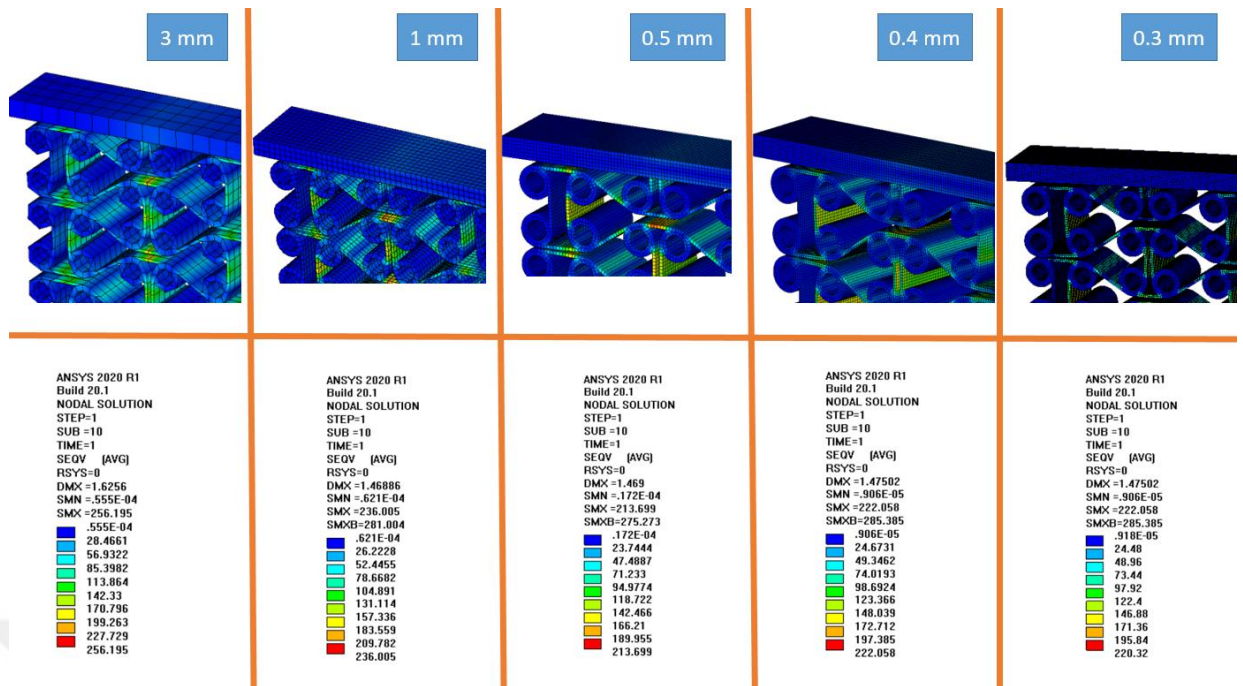


Figure 44: Equivalent Von Mises stress results under different mesh sizes.

4.2 Deformation Shapes and Results

Compression, tension and impact results are shared upcoming subjects. Furthermore, buckling results are also added; due to the fact that system is faced with compression. Before showing results, used boundary conditions are shared in Figure 45. The whole structure is fixed at bottom end and load/or displacements are applied on top end.

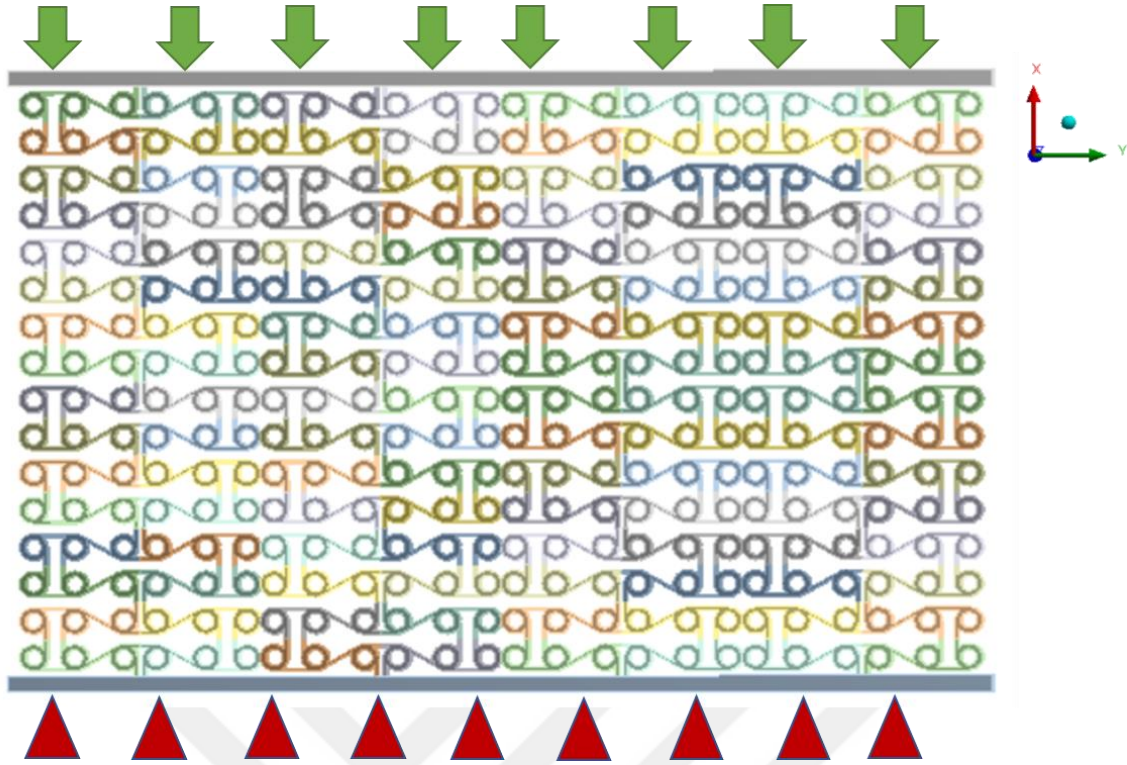


Figure 45: Boundary conditions in the structure.

As shown in Figure 45, red triangles represent the fixed location, and green arrows represent the load and/or displacements on the whole structure.

4.2.1 Compression results

All design variations are solved with same amount of displacement for to get compression response for each structures. At the end of each results, the Poisson's ratios and stiffness per unit mass values are compared. The comparisons are made for the design names which are listed in Table 3 before. Deformation shape with undeformed shape is illustated for the default novel auxetic metamaterial in Figure 46.

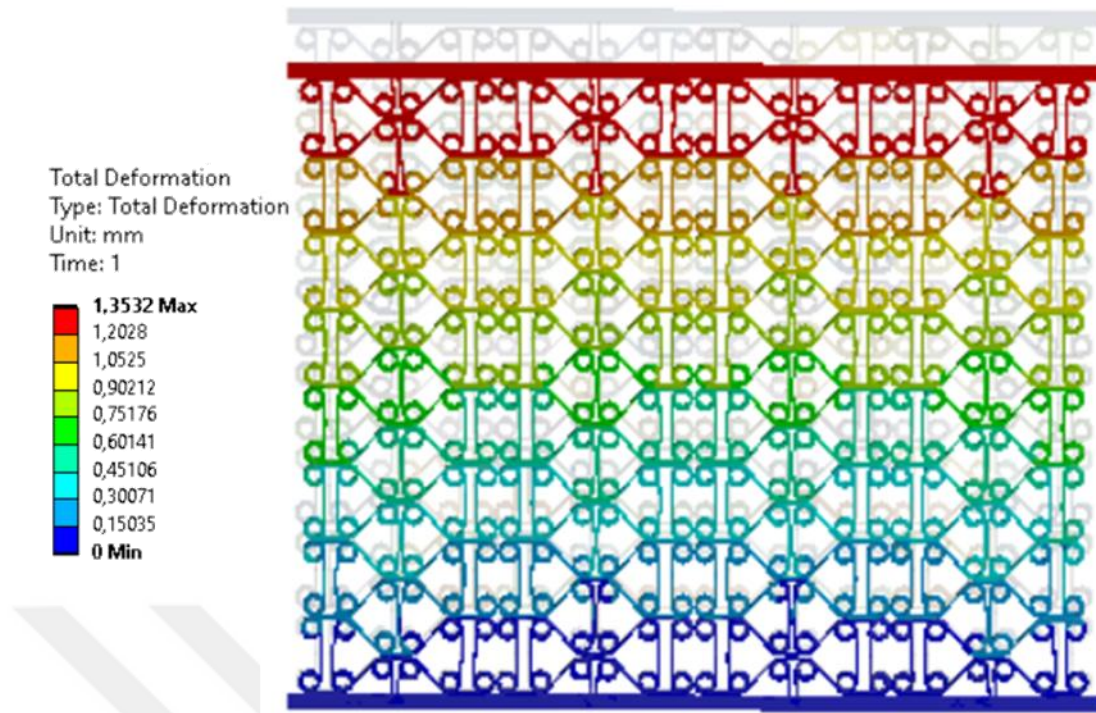


Figure 46: Deformation shape with undeformed model during compression.

As can be seen on Figure 45, in case of compression the structure does not run away from the load application direction, but concentrate towards to centre. Additionally, equivalent Von Mises stress results are shared in Figure 47.

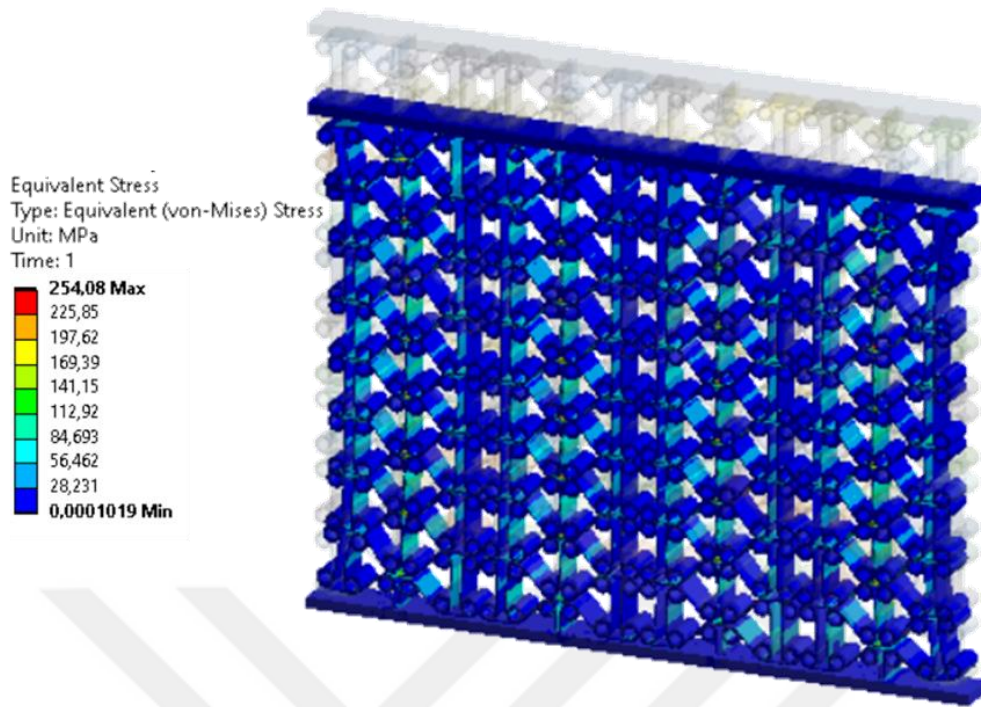


Figure 47: Equivalent stress results under compression.

Poisson's ratio change during $-x$ direction of displacement results for compression case are shared in Figure 48 as a graph.

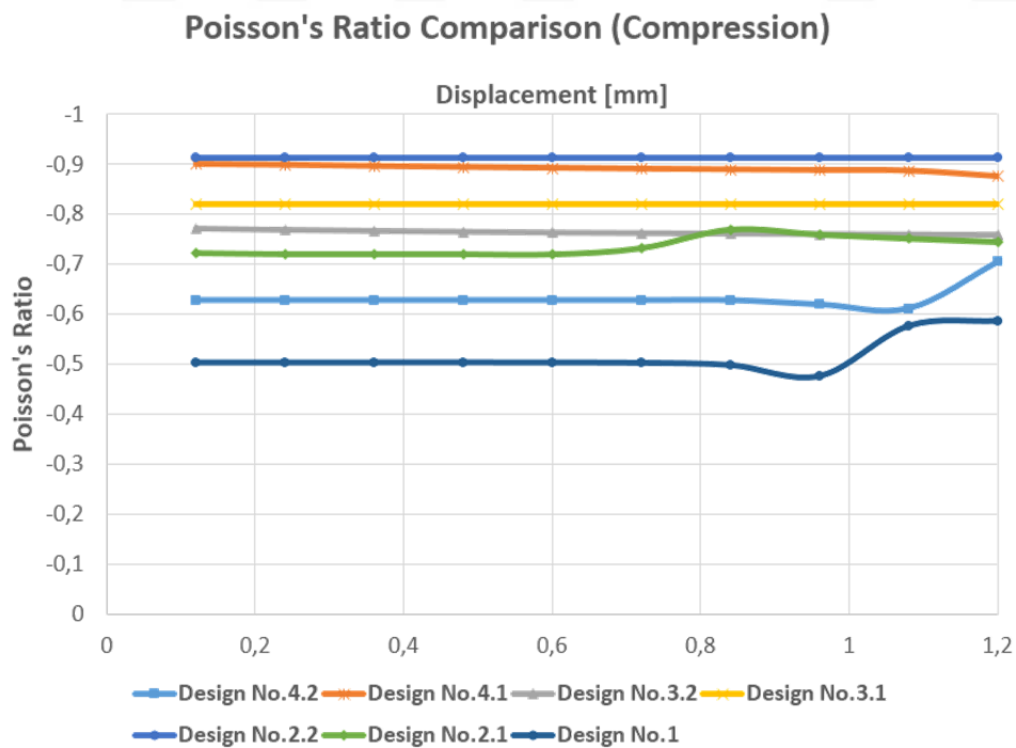


Figure 48: Poisson's ratio comparison – Compression situation.

When the default geometric parameters are changed, it is obvious that negative Poisson's ratio increases. Especially, increasing hole diameter dimension has a great impact on NPR. In Figure 49, stiffness per mass distribution is illustrated under $-x$ direction of compression.

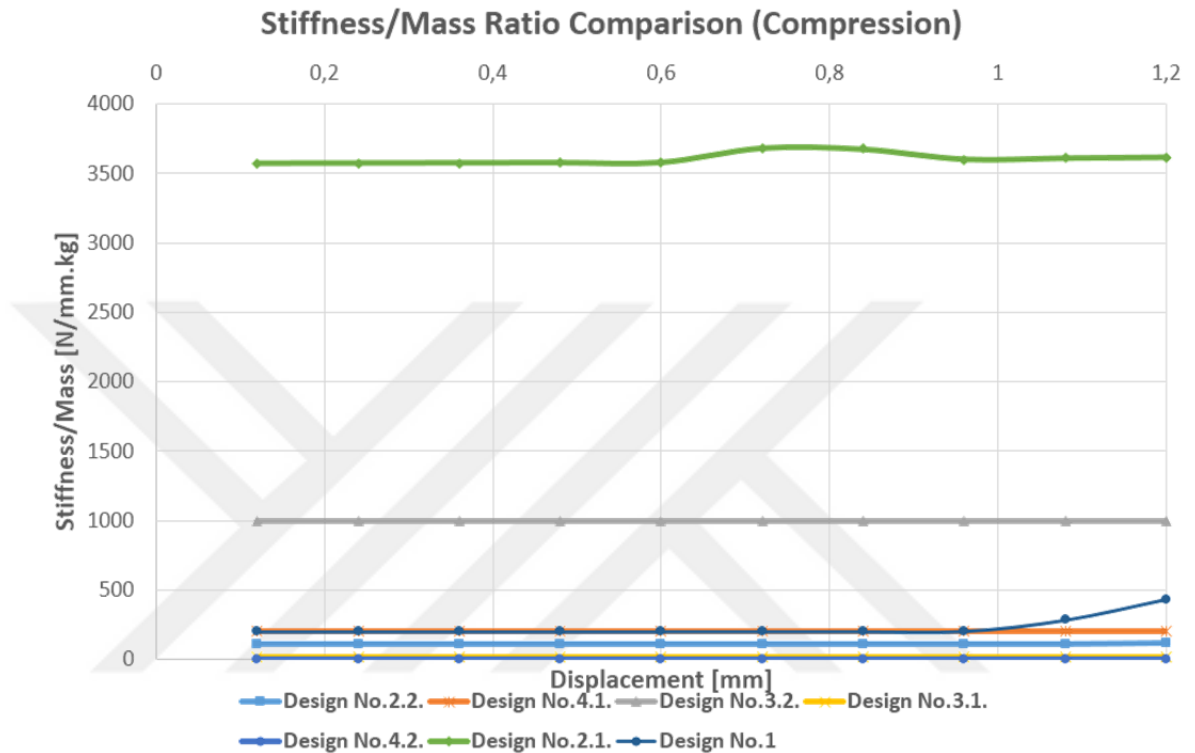


Figure 49: Stiffness per mass comparison – Compression situation.

Decreasing hole diameter significantly impact the stiffness behaviour of the structure among the other designs.

4.2.2 Tension results

Similar to compression analyses, same amount of displacements (1.2mm) are applied in tension direction for each designs. In case of tension, deformation shape is showed in Figure 50.

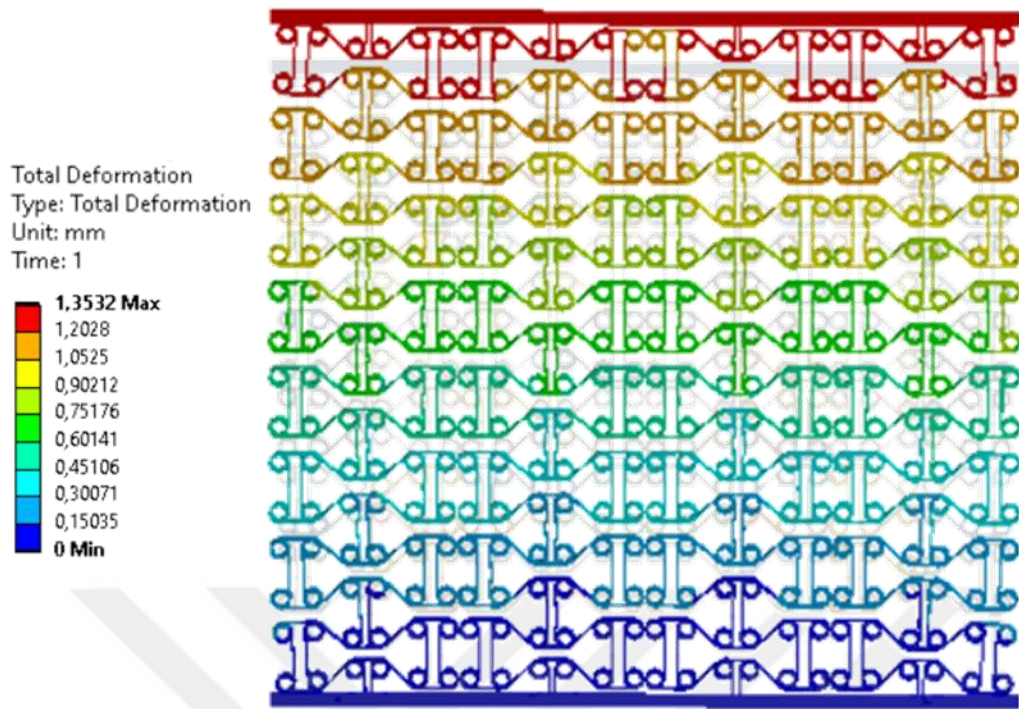


Figure 50: Deformation shape with undeformed model during tension.

During tension novel auxetic structure behave like increasing area through lateral cross section. Also, equivalent Von Mises stress results are shared for tension situation in Figure 51.

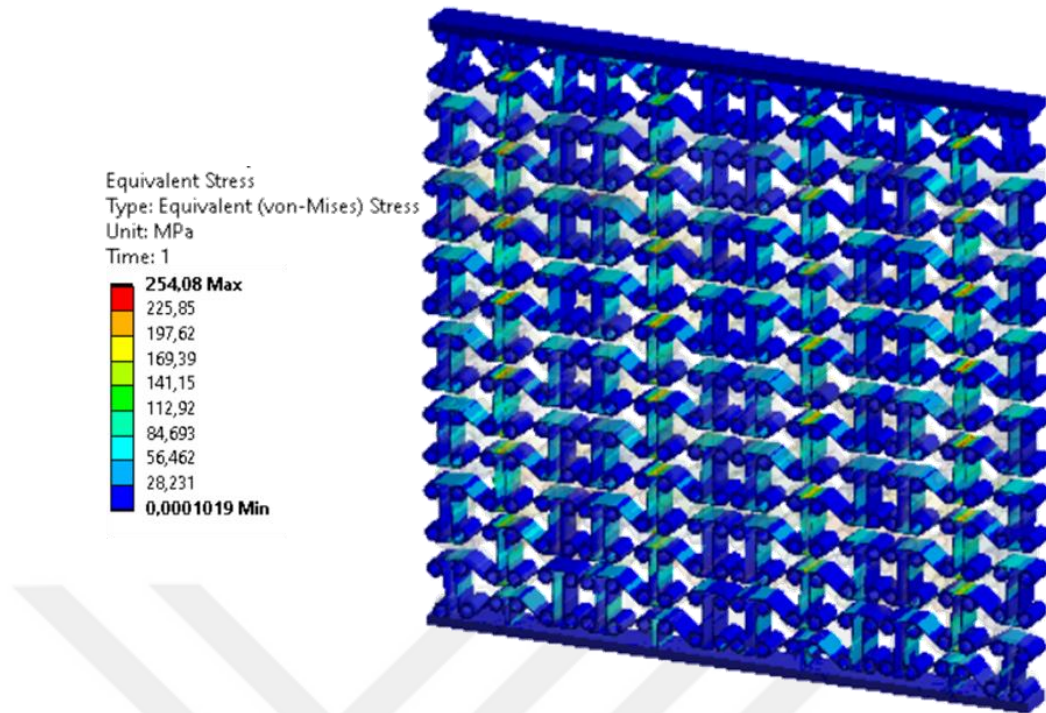


Figure 51: Equivalent stress results under tension.

In other words, structure is not contracting, but expanding. Poisson's ratio results for tension is added in Figure 52 for +x direction of displacements.

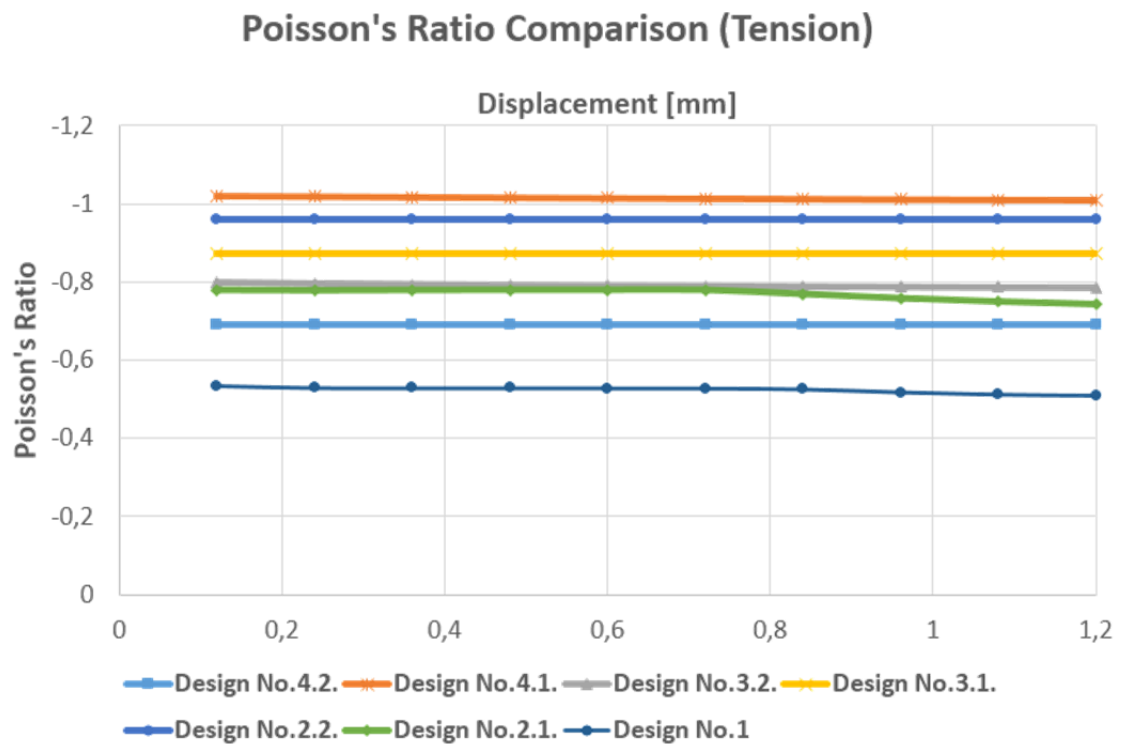


Figure 52: Poisson's ratio comparison – Tension situation.

All of the design changes according to geometric parameters changings, negative Poisson's ratio levels are affected in positive manner in case of tension. As a result of tension; the stiffness per mass values are shared in Figure 53.

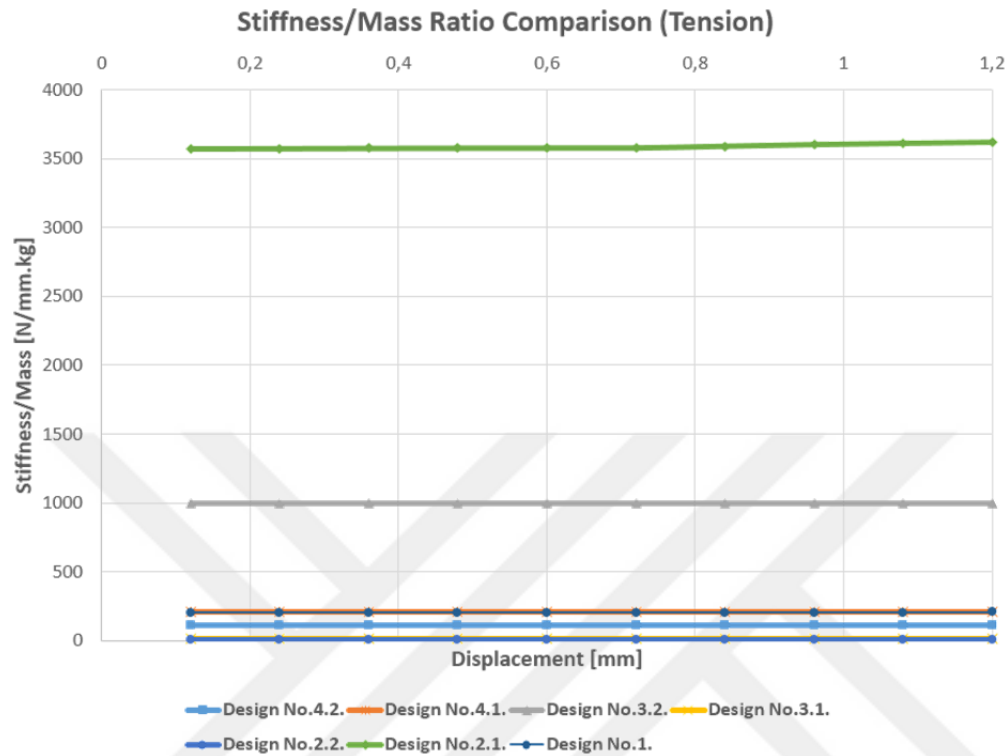


Figure 53: Stiffness per mass comparison – Tension situation.

It can be seen from the results from the both compression and tension displacements, changing one of the three design parameters will enhance negative Poisson's ratio and stiffness per mass values, respectively.

4.2.3 Impact energy absorption results

As in tensile and compression analyses, low carbon steel was chosen as the material for impact analysis. The material properties are used as before, the values shown in Table 4. Within the scope of impact analysis, vertical movement at certain speeds was given on the upper plate of the structure with additional structure. The degrees of freedom in all directions except the vertical direction of the moved plate are zeroed.

The part that will be in motion within the scope of impact analysis is a rigid plate. The analysis was repeated as the speed of the rigid plate was 8000 mm/s, 8500 mm/s and 9000 mm/s, thus the effect of different speeds on the results was demonstrated comparatively. As a result of this analysis, it was aimed to have information about the

impact absorption feature of the structure. Explicit FE model and deformed shape are showed in Figure 54. There is a 20 mm distance between additional top structure and assembly and total 12 mm deformation is occurred. It is aimed that to see internal energy absorption by seeing each impact steps respectively.

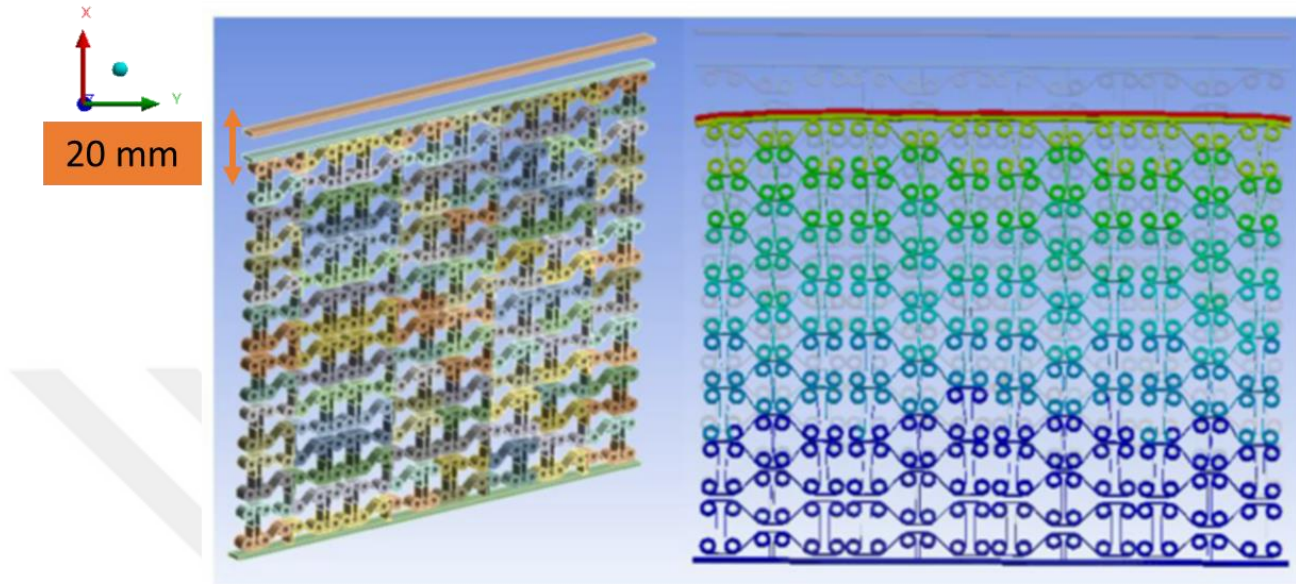


Figure 54: Explicit FE model and deformation after impact.

Boundary conditions are same for impact model as shown in Figure 45. Additionally, impacted structure has also fixed in both Y and Z directions; it is only free in X direction. Internal energy absorption results are showed in Figure 55 for three different impact speeds.

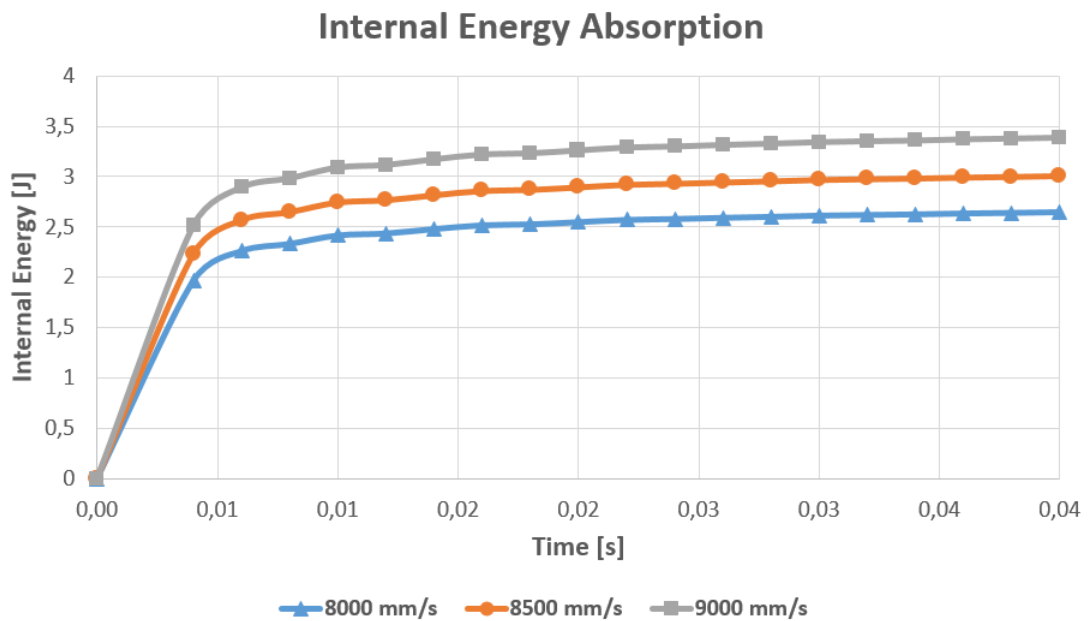


Figure 55: Internal energy absorption results.

As a result of this analysis, it was aimed to have information about the impact absorption feature of the structure. During the design phase, by making various changes to the original auxetic design model, if the structure is kept in the elastic region, a structure with the potential to be exposed to a large number of impacts can be created, which offers more variety in terms of use.

4.2.4 Buckling results

Designs are required to have high resistance to buckling damage. Although the parts theoretically appear to bear quite large compressive stresses, they may suffer buckling damage and lose their function before reaching this level. Therefore, the buckling resistance of designs and the amount of load that buckling damage will occur should be as large as possible. Under 100N compression load the equivalent stress distribution is showed in Figure 56.

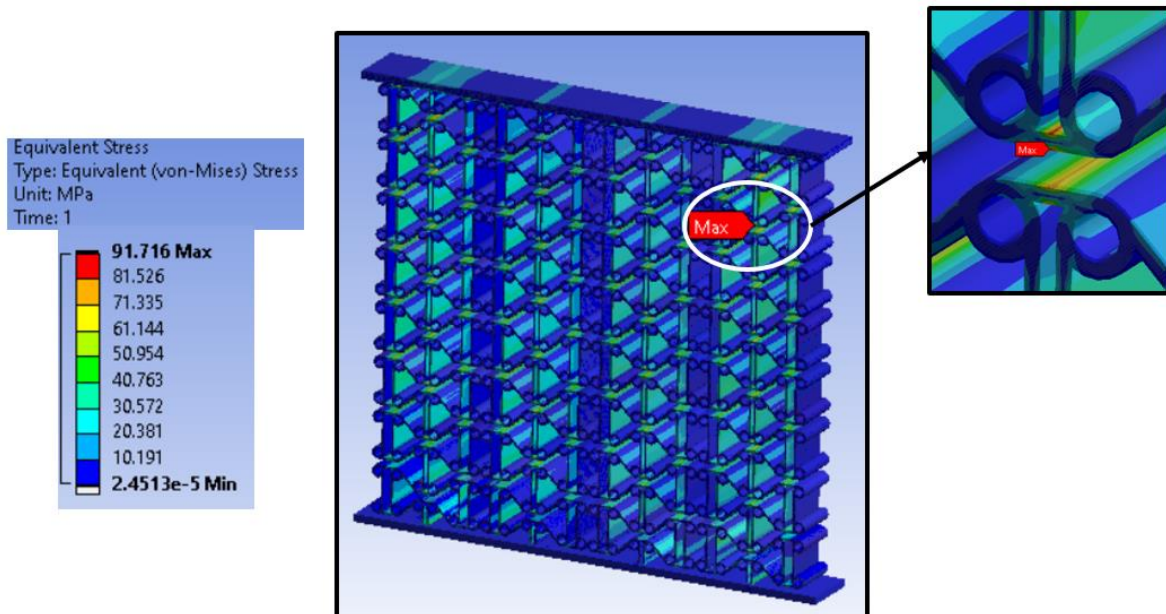


Figure 56: Von-Mises stress distribution.

The novel design reaches the first buckling mode at 1300 N. The first buckling mode shape has a bending appearance. The mode shape illustrated in Figure 53.

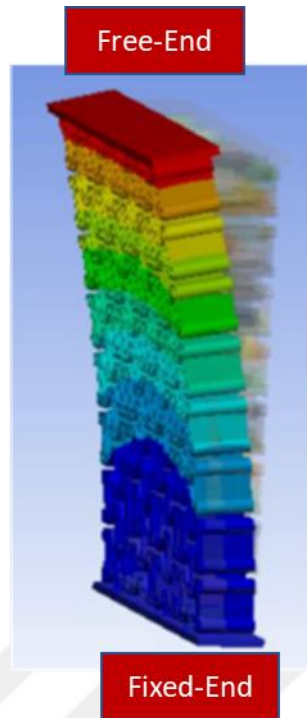


Figure 57: 1st Buckling mode shape and B.C.s of novel auxetic metamaterial.



5. CONCLUSION AND RECOMMENDATIONS

Today, with the constantly developing and renewed technology, there has been an increase in studies on metamaterials that are more durable but also lighter and have the potential to adapt much more to the texture in the area of use. One of them is auxetic materials.

The primary aim of this study was to design a new auxetic metamaterial with negative Poisson's ratio that will take place in the literature. Analyses carried out and obtained. With the data, it was seen that the three-dimensional structure has a negative Poisson's ratio. Therefore, the study has achieved its primary goal. However, the field of research can be deepened by studies on some subjects.

As a result of the analyses, it has been proven that the original Auxetic design shows NPR in itself and each geometry change. Also, changing the geometric parameters has been much more effective for NPR; these values converged to -1. These results increased the hope that the novel design will be used as a filling material in impact protective structures. It is aimed to concentrate the filling material towards the direction of the impact. With the novel design, a new perspective has been given to the literature in this area. In addition, the impact absorption energy property of the designed novel sandwich structure was also examined. In this context, the energies in the structure as a result of impacts applied at various speeds are shared. In order to examine the effectiveness of energy absorption values; it is needed to create real life models that are used in sports, defense and other industrial areas. It would be more accurate to model them to understand how the auxetic filler material behaves in real life situations.

Increasing the negative Poisson's ratio value of the auxetic structure can be considered in prospective studies. It can be investigated which parameters can be increased by making changes or the Poisson's ratio can be changed by designing a different model. Analyses can be repeated using different materials. With metal and nonmetal materials, the behavior of the lattice structure can be measured and thus potential uses can be determined more accurately. Various structural defects can be included in the modeling. No structure is perfect, and while some defects in the structure create disadvantages, others provide advantages. When possible flaws are included in the analysis, it is possible to obtain more realistic results. No prototype was produced

within the scope of this study. The designed structures can be produced as prototypes and tested. Thus, both test and analysis results can be compared and verified.



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