A study on Auxetic material to determine effective modulus for biomedical applications

A thesis submitted towards partial fulfillment of the requirements for the degree of

Master of Engineering in Mechanical Engineering

Submitted by

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Examination Roll No:
M4MEC24009

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CERTIFICATE OF RECOMMENDATION

This is certified that the thesis entitled **" A study on Auxetic material to determine effective modulus for biomedical applications"** is a bonafide work carried out by NAWAJ SHARIF under my supervision and guidance for partial fulfillment of the requirement for post graduate degree of Master of Engineering in Mechanical Engineering during the academic session 2023-2024

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<u>CERTIFICATE OF APPROVAL</u>**

This foregoing thesis is hereby approved as a creditable study of an engineering subject carried out and presented in a manner satisfactory to warrant its acceptance as a pre-requisite to the degree for which it has been submitted. It is understood that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein but approve the thesis only for the purpose for which it has been submitted.

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<u>DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS</u>

The author hereby declares that this thesis contains original research work by the undersigned candidate as part of his Master of Engineering Mechanical Engineering studies during academic session 2023-2024.

All information in this document has been obtained and presented in accordance with academic rules and ethical conduct.

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ACKNOWLEDGEMENT

First and foremost, I thank almighty for giving me the ability and patience and blessing me with success to complete this thesis.

I would like to gratefully thank my academic supervisors, Prof. Amit Karmakar and Dr. Apurba Das; it is truly a pleasure working under them, for their unlimited support, continuous encouragement and durable patience during my project. Because of their close supervision and great knowledge and professionalism I have experienced a significant event in my life with a positive effect to a promising future.

I would also want to express my gratitude to my lab seniors and research scholars, Masud Rana and Abhishek Gupta for making this journey a happy and a joyous one.

Finally, special thanks to my parents for encouraging me while I am far away from them & for their patience, time and understanding.

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Chapter 1

1. Introduction

1.1 Need of Biomedical Implant

The rapid developments in biomedical implant design necessitate the use of smart and high-performance materials to meet the ever-increasing demands in patient specific applications. Biomechanics is embracing a variety of materials, including as ceramics and polymers, in addition to the well-established function of metals in the area. Metals offer strength and biocompatibility, ceramics resist wear and replicate the rigidity of bone, and polymers are versatile enough to allow for both elasticity and porosity. Each has its own advantages. But ceramics break easily, metals can insulate against stress and are costly, and polymers raise questions regarding their biocompatibility and long-term endurance. Investigating substitute materials could lead to patient-specific implants with improved functionality, more tissue compatibility, and more affordable options for increased healthcare accessibility.

Auxetic implants, with their unique ability to expand under tension, offer several advantages over traditional implants. The expanding nature of auxetic structures mimics the natural porosity of bone, potentially promoting better bone-implant contact and osseointegration (Huang et al.,2018). Their ability to deform under load can distribute stress more evenly, potentially reducing stress shielding and improving implant longevity (Liu et al.,2017).Much of the current research on auxetic implants focuses on porous structures. These porous auxetic implants aim to combine the benefits of auxetic behaviour with the advantages of osseointegration offered by porosity. While porous auxetic implants hold promise, there are limitations. Creating intricate porous structures can be expensive and technically challenging (Zhang et al.,2018). Porosity can increase the risk of bacterial colonization and infection (Darouiche et al.,2004).

Non-porous auxetic implants offer a potential solution by simpler design could reduce production complexity and a solid surface could minimize bacterial attachment. Here lies the opportunity:

- Investigate the effectiveness of non-porous auxetic designs for reducing stress shielding and tailored stress distribution.
- Explore alternative manufacturing methods for cost-effective production.

- Evaluate the long-term biocompatibility and performance of non-porous auxetic implants in vivo.

The high cost of titanium auxetic implants, as mentioned in the passage, creates a barrier to patient access. Non-porous auxetic implants, potentially made from more affordable materials, could address this by Simpler designs may be manufacturable using less expensive materials. More affordable implants could benefit a wider range of patients. On-porous auxetic implants represent a promising avenue for research. They have the potential to offer the benefits of auxetic behaviour at a lower cost, potentially improving implant accessibility and patient outcomes. Further research is crucial to explore their effectiveness and unlock their full potential in the field of biomaterials.

1.2 Implant Biomaterials:

Materials used for implants, such as metals (Manam et al.,2017), ceramics (Catledge et al.,2002), and polymers (Halliday et al .,2012), are essential in the field of medical implants(Jing et al.,2020) Metals such as titanium and stainless steel are frequently used due to their superior mechanical strength and biocompatibility (Palmquist et al.,2010). These materials provide the stability and durability required for load-bearing implants (Moiduddin et al.,2019). Ceramics, like porous alumina, are ideal for dental and orthopedic applications because of their exceptional biocompatibility and wear resistance(Klawitter et al.,1977) Their high strength and low friction properties make them suitable for articulating surfaces (Camilo et al.,2017). Polymers, such as polyethylene (Sheikhhassani et al.,2015) and polyetheretherketone (Araújo et al.,2020), are lightweight and flexible options ideal for implants requiring elasticity or shock absorption (Lommen et al.,2022) (see Table 1).

Table- 1: Material used in biomedical implants.

Type	**Implant Materials**	**Chemical Composition or Abbreviation**
Metals	Titanium	CpTi
	Titanium Alloys	Ti-6A1-4 V
		Ti-6Al-7Nb
		Ti-5Al-2.5Fe

		Ti-15 Zr-4Nb-2Ta-0.2Pd
		Ti-29Nb-13Ta-4.6Zr
		Roxolid (83 %–87 %Ti-13 %–17 %Zr)
		Ti-6A1-4 V extra low interstitial (ELI)
	Tantalum	Ta
	Cobalt-Chromium Alloy	Vitallium, Co-Cr-Mo
	Gold Alloys	Au Alloys
	Stainless Steel	SS, 316 LSS
Ceramics	Alumina	Al_2O_3,polycrystalline alumina, or single-crystal sapphire
	Hydroxyapatite	HA, $Ca_{10}(PO_4)_6(OH)_2$
	Beta-Tricalcium phosphate	β-TCP, $Ca_3(PO_4)_2$
	Carbon	C
		vitreous
		low-temperature isotropic (LTI)
		ultra-low-temperature isotropic (ULTI)
	Carbon-Silicon	C-Si
	Bioglass	$SiO_2/CaO/Na_2O/P_2O_5$
	Zirconia	ZrO_2
	Zirconia-toughened alumina	ZTA
Polymers	Polymethylmethacrylate	PMMA
	Polytetrafluoroethylene	PTFE
	Polyethene	PE
	Polysulfone	PSF
	Polyurethane	PU
	Polyether ether ketone	PEEK

1.2.1 Implant failure

Implant materials have good biocompatibility and are simple to customize for specific applications (Kurtz et al., 2007). Each implant material has distinct qualities that enable clinicians to choose the best material based on the implant's and the patient's demands. The synthesis process in implants is also crucial because it directly impacts the implant's performance and material properties (Osuchukwu et al.,2021). The desired mechanical strength, biocompatibility, and durability required for successful implantation are guaranteed by the precise synthesis of implant materials (Osuchukwu et al.,2008).

Numerous factors, such as osseointegration failure (Hossain et al.,2023a), biomechanical failure (Lee et al.,2021), infection (anchez et al.,2018), and nerve or tissue damage (Hossain et al 2023b), can lead to implant failure. Osseointegration failure refers to the inability of the implant to fully integrate and bond with the surrounding bone, resulting in implant instability and potential loosening or loss (Koka et al.,2012). Excessive loading or improper force distribution on the implant can lead to biomechanical loss by causing fractures, wear, or component dislodgment (Hsu et al.,2012). Inadequately controlled infection can also result in implant failure (chen et al.,2003). Inflammation, bone loss, and implant instability may occur during or after implantation (Nimbalkar et al.,2021). The placement of an implant may cause nerve or tissue damage, leading to pain, compromised functionality, or sensory or motor deficits (Delfini et al.,2015).

There are two types of implant failure: early and late implant failure, each with a unique set of causes (Manor et al.,2009). Early implant failure usually happens within the first few months (Kang et al.,2019). It can be caused by various things, including poor surgical technique, insufficient bone quality or quantity, the wrong implant being chosen, and systemic diseases like diabetes disorders (Apher et al.,2020). Contrarily, late implant failure takes place months or even years after successful implant integration and may be brought on by problems with the prosthesis (Shen et al.,2020), biomechanical overload (Smith et al.,11993), and peri-implantitis (inflammation and infection around the implant) (Dvorak et al.,2011).

1.3 Auxetic Structures: A Promising Solution:

While current implant materials offer biocompatibility and customization, they face challenges like osseointegration failure, biomechanical failure, infection, and nerve damage. This is where auxetic structures emerge as a promising solution.

1.3.1 Auxetic structure

Auxetic structures are a fascinating class of materials with the unique property of expanding when stretched in tension. This behavior stands in contrast to most common materials, which tend to become thinner in one direction when pulled in another. The unusual properties of auxetic structures hold great promise for various applications, particularly in the field of biomaterials.

Here's a breakdown of key aspects of auxetic structures:

- **Negative Poisson's Ratio:** This is the defining characteristic of auxetic materials. Poisson's ratio describes the proportional change in thickness (transverse strain) relative to the change in length (longitudinal strain) under tension. A negative value indicates that the material expands in the transverse direction when stretched.
- **Mechanisms:** The expansion in auxetic structures can be achieved through various mechanisms, such as rotating units, hinged connections, or re-entrant cellular pattern.
- **1.3.2 Overcoming traditional implant failure by Auxetic Implant:**
- **Improved Osseointegration:** The expanding nature of auxetic structures mimics the natural porosity of bone. This could potentially promote better bone ingrowth and a stronger implant-bone interface, leading to improved implant stability and longevity.
- **Enhanced Stress Distribution:** Their ability to deform under load can distribute stress more evenly throughout the implant and surrounding bone. This can help reduce stress shielding, a phenomenon where bone resorbs (weakens) due to taking on less stress from a stiff implant.
- **Reduced Micromotion:** A tighter fit between the implant and bone due to improved osseointegration might minimize micromotion, a small movement that can contribute to implant loosening and peri-implantitis (inflammation around the implant).

1.3.3 Types of Auxetic Implants:

Porous Auxetic Implants: These combine the benefits of auxetic behavior with the advantages of porosity for enhanced bone ingrowth. However, they can be more complex and expensive to manufacture, and may carry a higher risk of infection due to increased surface area.

Non-Porous or Multimaterial Auxetic Implants: These offer a simpler design, potentially reducing manufacturing costs and infection risk. They still retain the core advantages of auxetic structures related to osseointegration and stress distribution.

Current Stage and Future:

Auxetic implants are a relatively new area of research, and more studies are needed to fully understand their long-term performance and biocompatibility. However, the potential benefits they offer are significant, making them a promising avenue for the development of next-generation implants with improved functionality and patient outcomes.

1.3.4 Potential Drawbacks of Porous Auxetic Implants

While auxetic implants offer exciting possibilities for overcoming traditional implant failures, there are some potential drawbacks to consider, particularly for porous auxetic designs:

- **Manufacturing Complexity:** Creating intricate porous structures with auxetic properties can be challenging and expensive using current manufacturing techniques (Rusu et al.,2023). This can limit their widespread adoption.
- **Infection Risk:** Porosity can increase the surface area available for bacterial colonization, potentially increasing the risk of infection (Manam et al.,2017).
- **Limited Research on Porous Auxetic Failures:** Much of the current research on auxetic implants focuses on non-porous designs. The specific failure mechanisms and long-term performance of porous auxetic implants in vivo require further investigation (Catledge et al.,2002).
- **Possible Solutions and Future Directions:**
- **Exploration of Alternative Manufacturing Methods:** Research into more efficient and cost-effective methods for producing complex porous auxetic structures is crucial for wider clinical use (Halliday et al.,2012).

- **Surface Treatments for Infection Control:** Developing surface modifications that minimize bacterial adhesion on porous auxetic implants can mitigate the risk of infection (Jing et al.,2020).
- **Focus on Long-Term In Vivo Studies:** More research is needed to evaluate the long-term performance and potential failure modes of porous auxetic implants in real-world settings (Plamquist et al.,2010).

1.4 Enhancing Porous Auxetic Implants with Composite Designs:

- **Manufacturing Simplicity:** Non-porous or Multimaterialauxetic implants, by definition, lack the intricate structures of their porous counterparts. This can significantly reduce manufacturing complexity and potentially lower production costs, making them a more accessible option (Jung et al.,2012).
- **Reduced Infection Risk:** Eliminating porosity removes the concern of increased surface area for bacterial colonization. This could lead to a lower risk of infection compared to porous auxetic implants (Pjetursson et al.,2012).
- **Maintaining the Benefits:**
- While addressing the drawbacks of porous designs, non-porous auxetic implants can potentially retain the core advantages of auxetic structures:
- **Improved Osseointegration:** The expanding nature of auxetic structures, regardless of porosity, can still promote better bone ingrowth and a stronger implant-bone interface (Abduljabbar et al.,2022).
- **Enhanced Stress Distribution:** Their ability to deform under load can still distribute stress more evenly, potentially reducing stress shielding on surrounding bone and lowering the risk of biomechanical failure (Aghaloo et al.,2019)

1.5 Addressing the Challenges: Focus of this Thesis

This thesis aims to address these challenges by exploring the design, fabrication, and biomechanical evaluation of non-porous auxetic structures for biomedical implants. The focus on three-dimensional non-porous cubic structure are given to achieve auxetic behaviour using a porous auxetic structure which have negative poison’s ratio in all three direction (masud et al.,2023). By (optimizing the design for mechanical performance, exploring alternative materials], aims of this research is contribute to the development of auxetic implant for next generation that improved functionality, long-term benefits for patients, and potentially lower cost compared to traditional implant materials.

1.6 Organization of the thesis

This thesis starts with the introduction section, elaborating the background of research and stating the objectives of the present study in Chapter 1.

It is then followed by literature survey to present associated theory, methods and findings of past research in Chapter 2.

Chapter 3 gives details of the material and modeling.

Chapter 4 portrays the results and discussion.

Chapter 5 deals with concluding remarks with future scope

Chapter 2

Literature Survey

2.1 AUXETIC STRUCTURE

Over the past decades, different geometrical structures and models that can result in auxetic effects have been proposed, studied, and tested for their mechanical properties. Among the most important classes of such auxetic structures are 2 and 3 D re-entrant structures, chiral structures, rotating rigid/semi-rigid units, angle-ply laminates, hard molecules, microporous and liquid crystalline polymer.

These geometrical structures are extremely useful and important, as they can help researchers to understand better how auxetic effects can be achieved and how auxetic materials can be manufactured as well as how their properties can be optimized and predicted. A systematically review of these structures is given as follows.

2.1.1. Re-entrant structures

Gibson et al. (1982) proposed macroscopic auxetic cellular structures like 2D re-entrant honeycombs, consisting of 2D hexagons. Under uniaxial load, deformation occurs through diagonal rib hinging, causing horizontal alignment during stretching to cause vertical movement, resulting in an auxetic effect.

(Choi et al., 2023) examined the deformation behavior of re-entrant auxetic structures with a negative Poisson's ratio using experimental and numerical analyses. Results show that as the reentrant angle decreases, the Poisson's ratio increases, maintaining the auxetic property only when the re-entrant cell remains concave. Finite element analyses reveal similar results, especially in the concave deformation regime. Statistical analysis provides insights into re-entrant structures' deformation behavior.

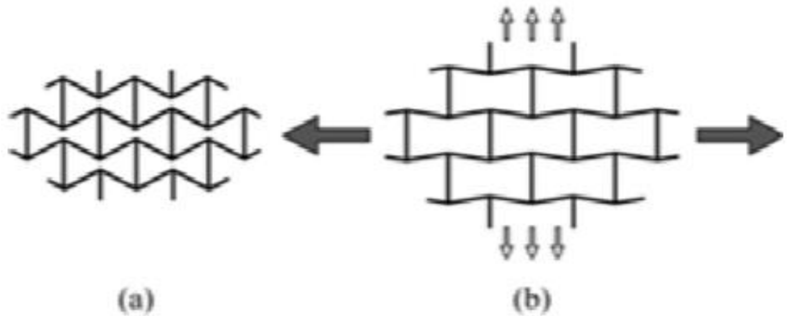

Figure 1. 2D Re-entrant honeycomb (a) Undeformed (b)Deformed

(Lian et al,.2023) presented a augmented double arrow honeycomb structures as re-entrant honeycombs with negative Poisson's ratio substructures to improve mechanical properties and energy absorption. It provides an analytical formula for collapse stress under quasi-static compression, failure stress under various densities and impact velocities, and dynamic crushing stress. Numerical simulations show that honeycombs with a second plateau period have superior energy absorption, making it an effective strategy for improving honeycomb impact resistance.

(Zhang et al,.2022) explored the use of additive manufacturing and laser cutting for fabricating auxetic metamaterials, addressing high costs and low efficiency. It examines the impact of wave radius, plate thickness, slot percentage, and base material on Poisson's ratio and mechanical performance. Results show that the assembled AACH has lower peak force and higher plateau stress compared to conventional assemblies. This cost-effective approach opens up broader applications for auxetic metamaterials.

(Alomarah et al,.2018) examined the impact of geometrical parameters on the in-plane tensile properties of a re-entrant chiral auxetic (RCA) structure. Finite element models were validated, and a parametric study assessed stress-strain curves and Poisson's ratio. Results showed that the structure deforms primarily through bending, stretching, and rotation of cylinders. Geometrical parameters significantly affect stress-strain curves and Poisson's ratios, providing insights into the structure's mechanical response under uniaxial tensile loading.

(Khan et al ., 2015) presented the mechanical behavior of a metallic re-entrant honeycomb auxetic structure made using laser-assisted Direct Metal Deposition (DMD) additive manufacturing. The structure's effective modulus and Poisson's ratio were estimated and validated using finite element analysis, indicating that DMD is an effective method for creating complex structures for various engineering applications. Auxetic effects can also be obtained from other reentrant structures (Larsen et al., 1997), as shown in Figure 2. Opening or closing of the arrowheads and stars respectively in double arrow-head structure (Larsen et al., 1997) (Figure 2a) This paper introduces a new method for designing and fabricating compliant micromechanisms and material structures with negative Poisson's ratio (NPR). The process uses automated numerical topology optimization methods, allowing users to specify elastic properties and geometrical advantages. The fabrication involves patterning silicon on plasma-enhanced chemical vapor deposition (PECVD) glass, etching the structures, and underetching in a two-step reactive ion etching (RIE) process. Components are tested using a probe, enabling rapid prototyping and testing. The computational design tool allows for the creation of topology-optimized structures, allowing for fast prototyping.

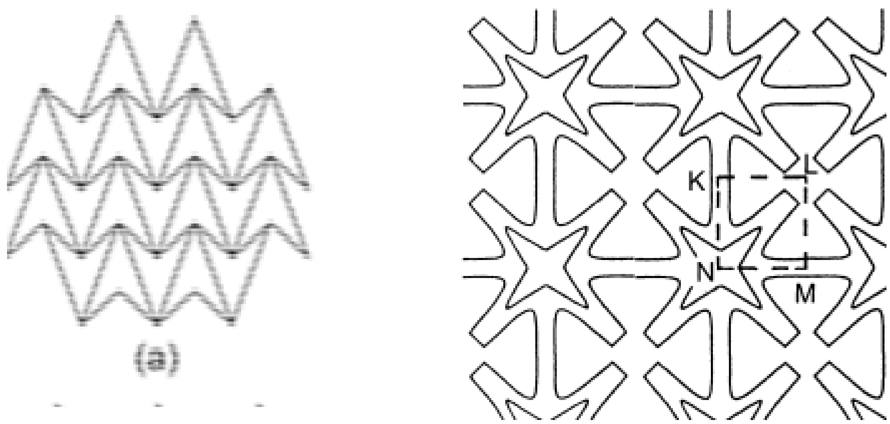

Figure 2. (a) Double arrow headstructure , (b) Star honeycomb structure

(Theocaris et al., 1997;) explored the negative Poisson's ratio in materials and composite structures, a phenomenon that has been proven analytically for continuum materials and certain mechanisms (as shown in Figure 2b). It uses numerical homogenization theory to explore the impact of microstructural characteristics on the structure's overall elastic moduli and behavior. The paper introduces composite materials with nonhomogeneous and isotropic microstructures, which can be treated as quasi-homogeneous and isotropic on the macro scale. The paper highlights the advantages of using materials with negative Poisson's ratios, such as reducing stress concentration factors and facilitating cold metal forming processes. The study demonstrates that the shape of micro-inclusions significantly influences this phenomenon.

Poisson's ratio in materials is influenced by microstructure factors like rotational degrees of freedom, non-affine deformation kinematics, and anisotropic structure. Non-affine kinematics and non-central forces combined with pre-load can lead to negative Poisson's ratios in isotropic materials. Chiral microstructures with non-central force interaction or deformation can also exhibit negative Poisson's ratio. Understanding and manipulating these microstructural characteristics is crucial for tailoring material properties to meet specific performance requirements.

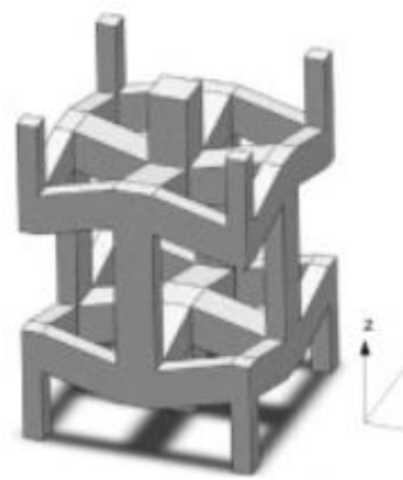

Figure 3. Structurally hexagonal re-entrant honeycomb

(yang et al.,2015) developed an analytical model for a 3D re-entrant honeycomb auxetic cellular structure, using large deflection beam and Timoshenko beam models. The model provides solutions for modulus, Poisson's ratios, and yield strength in all principal directions, demonstrating significant mechanical property control through geometric designs. Comparison with experimentation and finite element analysis confirmed the model's convenience and accuracy in performance prediction, especially when manufacturing-related factors are incorporated. However, higher-order coupling effects, such as warp locking, reduced the model's accuracy, particularly under lower structural symmetry. Experimental studies with Ti6Al4V samples were conducted to verify the theoretical modeling, extending discussions to design for additive manufacturing of cellular structures.

2.1.2Chiral structures

Cellular solids, particularly honeycomb structures, are widely used in engineering due to their lightweight and strong properties (Prall et al.,1997). However, advancements in manufacturing processes have made these materials more accessible to other industries. Interest has grown in re-entrant structures, unique honeycombs, and foams with negative Poisson's ratios, which contradict the conventional assumption that Poisson's ratios are positive. Honeycombs with inverted cells yield negative Poisson's ratios in-plane, and foam materials with negative Poisson's ratios, such as polymer and metallic foams, can also be developed. Other structures with negative Poisson's ratios include hinged frameworks and linked structures.

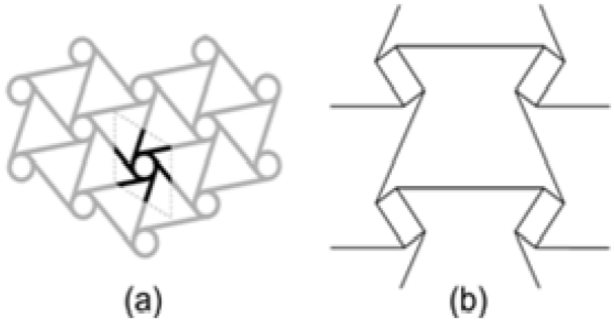

Figure 4. Chiral honeycombs (a) Formed with the same chiral units(b) Formed with symetrical chiral units.

(Nečemer et al.,2020) presented a 3D numerical simulation of the mechanical behavior of a chiral auxetic cellular structure under multiaxial loading conditions. The study focuses on understanding how the geometry of the unit cell affects Poisson's ratio and deformation behavior. A 3D computational model is constructed using beam finite elements within the LS DYNA software framework, simulated hydro-compression loading conditions, and interactions between contacting surfaces. The model provides insights into the deformation behavior, including damage, and enhances understanding of the structure's crushing behavior under multiaxial loading. The study builds upon previous research, which investigated deformation behavior and Poisson's ratio across various geometries of chiral auxetic structures. The computational analyses show that the auxetic effect is more pronounced with higher amplitudes and smaller cell lengths.

2.1.3Rotating units

(Ruben et al., 2005) proposed the potential of auxetic behavior in 'connected stars', a new class of structures consisting of star-shaped units interconnected to form two-dimensional periodic structures. The study uses the EMUDA technique for efficiency and ease of analysis. Auxetic materials and structures exhibit unusual properties, such as expansion under tension and contraction under compression. The study evaluates various two-dimensional periodic structures using the EMUDA technique, aiming to understand the factors contributing to the presence or absence of a negative Poisson's ratio in these systems.

The discussion discusses the auxetic behavior in materials with a negative Poisson's ratio, which offers advantages like increased shear stiffness, improved indentation resistance, and better acoustic damping. The Poisson's ratio varies with strain and initial geometry parameters. The deformation of triangles during rotations reduces the auxetic effect, but force-field simulations show it persists, highlighting the effectiveness of rotating triangles in real materials.

Auxetics exhibit the unusual property of expanding when uniaxially stretched (negative Poisson's ratio), a property that is usually linked to geometric features and deformation mechanisms. One of the mechanisms leading to auxetic behavior is the rotation of rigid units; systems composed of triangles, squares, or rectangles have already been studied for this mechanism. In this work this study extended by considering systems which can be constructed from either connected rhombi or connected parallelograms. Various types of such systems can exist and a detailed discussion are made for the properties of one type of ‘rotating rhombi' and one type of ‘rotating parallelograms. The Poisson's ratio of these systems can be positive or negative, is anisotropic and dependent on the shape of the parallelograms/rhombi and the degree of openness of the system.

2.2 Composite Structure

(Milton et al., 1992) revealed the existence of two-dimensional composite materials with hexagonal symmetry and Poisson's ratios close to -1. The study also reveals that as r approaches 0, the Poisson's ratio approaches -1, indicating uniform deformation on a macroscopic scale. A second family of composites with lower Poisson's ratios is obtained by introducing additional microstructure. The study also shows that elastically isotropic composites can be created by layering components on different length scales.

(Senatovet al., 2023) presented a method for modeling a biomedical device, specifically an interbody cage, using CAD software. The mechanical properties of experimental prototypes of Ti-6Al-4 V cages were characterized through computer modeling, static, and low-cycle fatigue compression tests up to 3500 cycles. The study found that 3D printed cells with an angle of inclination less than 90˚ (auxetic metamaterial) exhibit higher static compressive strength and fatigue resistance compared to cells with an angle greater than 90˚ (honeycomb structure). The auxetic-based cage has a Young modulus of 6.68 ± 0.28 GPa, similar to human cortical bone's elastic modulus.

(Peng et al., 2024) studied the design of auxetic 3D interlocking brick-and-mortar composites inspired by nacre, a natural material known for its strength and resilience. Through finite element simulations and computational homogenization, the composites show tunable negative Poisson's ratios when tailored to their microstructures. The study also demonstrates that by rationally designing the microstructure and selecting appropriate base materials, these composites can achieve auxetic properties. The study suggests these composites hold promise for various engineering applications due to their high fracture toughness and auxeticity.

2.3 Biomaterial

Titanium

(Mondal et al,.2022) demonstrated the use of titanium alloy in orthopedics due to its biocompatibility and increasing demand. Porous structures, manufactured through additive manufacturing processes like selective laser melting (SLM), are crucial for bone tissue engineering. Seven different Ti6Al4V porous scaffolds were designed and fabricated using SLM. Process parameters like laser power and scanning speed influence defect behavior and morphology. The grid structure exhibits superior manufacturing ability and lower surface roughness.

(Wang et al,.2023) introduced a titanium auxetic bone screw (AS) to address screw loosening and migration issues in orthopedic surgery. AS improves primary screw-bone fixation stability, but its porous structure affects fatigue behavior and in vivo longevity. Results show AS has lower fatigue strength but better osseointegration performance, especially under in vivo tensile loading. This research highlights the potential clinical application prospects of AS in orthopedic surgery, providing theoretical guidance for design optimization and clinical use of auxetic bone screws.

PEEK

(Flejszar et al., 2022) study explored the use of low parts per million atom transfer radical polymerization (ATRP) methods to enhance the biocompatibility of Polyetheretherketone (PEEK) for bone implants. The researchers grafted hydrophilic polymer brushes onto PEEK to create a nanoscopic hydroxyapatite-polymer layer on the implant surface. The results confirmed that RDRP techniques can hydrophilize PEEK materials, leading to tailored properties. The study also confirmed the presence of grafted polymer chains through visualization techniques and confirmed the formation of a homogeneous hydroxyapatite-polymer layer.

Large bone defects from tumors and trauma are often addressed through autogenous bone transplantation, but this method has limitations (Hongyun et al., 2021). Advancements in orthopedic implants and bone tissue engineering materials, particularly polyether-ether-ketone (PEEK), offer potential solutions. PEEK materials offer non-toxicity, high-temperature resistance, corrosion resistance, abrasion resistance, high strength, toughness, X-ray radiolucency, and excellent sterilization performance. They have been successfully used in clinical practice with efficacy and widespread recognition. This review reviews progress in performance requirements, material development, and surface modification of PEEK as an orthopedic implant.

2.4 Multi-material

A research presented by (Gao et al.,2024) on 3D origami-inspired auxetic honeycomb with high stiffness, overcoming the limitations of traditional materials. The honeycomb is made of high-performance continuous carbon fiber reinforced composite (CFRP) through hot-pressing molding, and its compressive elastic behaviors are experimentally evaluated. Results show that the CFRP honeycomb outperforms traditional 3D auxetic materials in multi-axial loading and rapid manufacturing, and exhibits nearly isotropic Poisson's ratio, making it suitable for applications requiring high load-bearing capacity and significant auxetic effect.

A new method to improve the stiffness of lightweight soft robotic bodies made from elastomer materials is presented by (Kaur et al., 2019). The solution involves architectured robotic bodies with deformable cellular structures that are easy to fabricate, lightweight, and mechanically durable. These structures overcome stiffness limitations and other drawbacks of conventional soft bodies, such as high pressure or impact damage. The study includes the development of an artificial cellular finger with embedded pressure sensors, enabling a functional system through multi-material 3D printing. The integrated grippers demonstrate strong gripping capabilities, with a maximum force of 16 N upon actuation.

(Zhen et al.,2022) presented a method for designing three-dimensional auxetic microlattices to overcome limitations in their development and practical application. Current designs lack isotropy, limiting their applications. The authors use a density-based topology optimization method to distribute solid materials within a cubical design domain, ensuring elastic cubic symmetry. The microlattices are expected to exhibit desired properties, including elastic isotropy, negative Poisson's ratio, and zero thermal expansion. The method's effectiveness is demonstrated through numerical simulations using finite element analysis.

(Afshar et al.,2022) examined the design and analysis of architected bi-material auxetic plates, non-porous structures with auxetic behavior. The plates consist of rigid rotary units and soft inclusions, with varying design parameters affecting their mechanical properties. The research investigates natural frequencies and deflection under uniform lateral loading and evaluates the effectiveness of a homogenization technique in predicting dynamic and static responses. The aim is to explore industrial applications and develop predictive methods for these structures.

(Zhang et al 2020) investigated the design and mechanical behavior of interpenetrating composites with different types of auxetic fiber networks, which aim to achieve positive, negative, or zero Poisson's ratios. These composites are suitable for various engineering applications, such as aerospace, where high stiffness and energy absorption are required. The research examines the influence of fiber volume fraction, elastic properties, concavity of fibers, and structural hierarchy on the mechanical properties of these composites through computational simulations.

(Peng et al ., 2020) explored the effect of constituent materials on the elasticity of a two-phase composite with an infilled re-entrant honeycomb microstructure, revealing that even non-auxetic materials can induce auxeticity if the Young's modulus contrast between the phases exceeds a critical threshold. The research also identifies a phase-contrast-mediated switch of auxetic mechanism, where auxeticity arises from a conventional re-entrant mechanism and from microscopic sliding under macroscopic axial loading.

2.4 Research Gap and Present Scope

Many different types of composite are study in this paper are made like non porous and their elastic properties almost isotropic. Because of their negative Poisson’s ratio behaviour, the unique indentation response of these auxetic composite makes them ideal materials for impact resistance applications (Evans et al.,200) such as helmet and body armour (Sanmi et al.,2014). As the Poisson’s ratio of those composites can be tuned to zero or any-value near zero, they can be used in biomedical applications to imitate the Poisson’s ratio of bones, tissue or joints of human body (Stavroulakiset al.,2005) , or used to produce micro-sized robot to clean the vein in human body because they can reduce the lateral expansion under the thrust/ drag force (Evans et al.,2000) to enable the desired auxetic function in applications, the composites should have a sufficiently large stiffness.

Although there has been a lot of research on materials with negative Poisson's ratio (auxetic behavior) in cellular/porous structures (Lake et al.,1987) and anisotropic materials (Baughman etal.,1998), these methods frequently have drawbacks. Even with a high negative Poisson's ratio, cellular materials are softer and weaker. Although some 2D materials (hou et al.,2008) and single crystals (Grima etal.,1912) also show auxeticity, they are usually anisotropic and difficult to make in large numbers, which makes them impractical for use in practical applications. Hence, in the present study an attempt has been made to see the effects of different parameters on the auxetic structure and based on the specific cases this structure can be used for actual applications.

Chapter 3

Material and Modelling

3. GEOMETRIC STRUCTURES AND COMPUTATIONAL METHODS

3.1 Geometric structures

This thesis investigates the effective modulus and Poisson's ratio of a composite material composed of a 3D re-entrant honeycomb structure (Figure 5a) as reinforcement within a cube-shaped matrix (Figure 5b). (Rana et al.,2023) study the mechanical properties as poisson's ratio of the 3d re-entrant honeycomb and it shows negative poisson's ratio in all three direction. In this study insert the 3d re-entrant honeycomb as reinforcement fiber in a matrix cube. The resulting structure is a composite with two different materials.

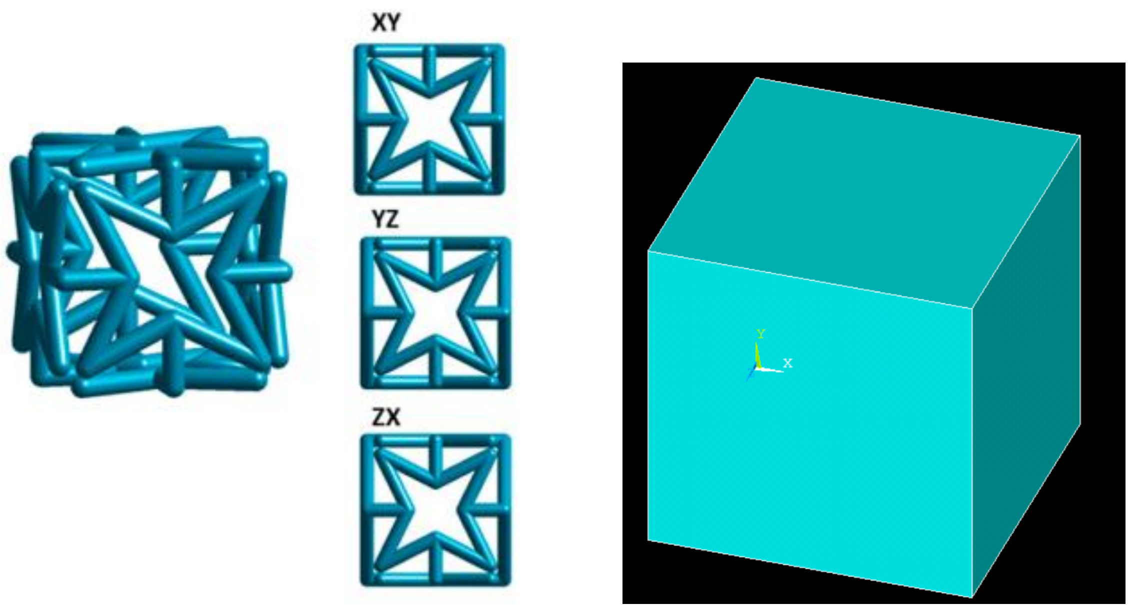

Figure 5 (a) 3D Re-entrant honeycomb (b) Cubic Matrix

The study comprises two main aspects in Case-1, the matrix properties are fixed as PEEK material, while the Young's modulus of the reinforcement material is varied from that of PEEK to Titanium in 32 steps. Additionally, the diameter of the re-entrant honeycomb structure that is the reinforcement fiber is varied across 10 different sizes. This results in a total of 320 observations. In case 2, the reinforcement material is fixed as Titanium, and the Young's modulus of the matrix material is varied from 3500 MPa to 100 MPa in 35 steps. Like the first aspect, the diameter of the re-entrant honeycomb structure is varied across 10 different sizes, resulting in a total of 350 observations. Through these comprehensive investigations, the aim is to understand the influence of varying material properties and honeycomb geometry on the effective modulus and Poisson's ratio of the composite material. Composite of 3d re-entrant honeycomb and cubic matrix is shown in figure 5c

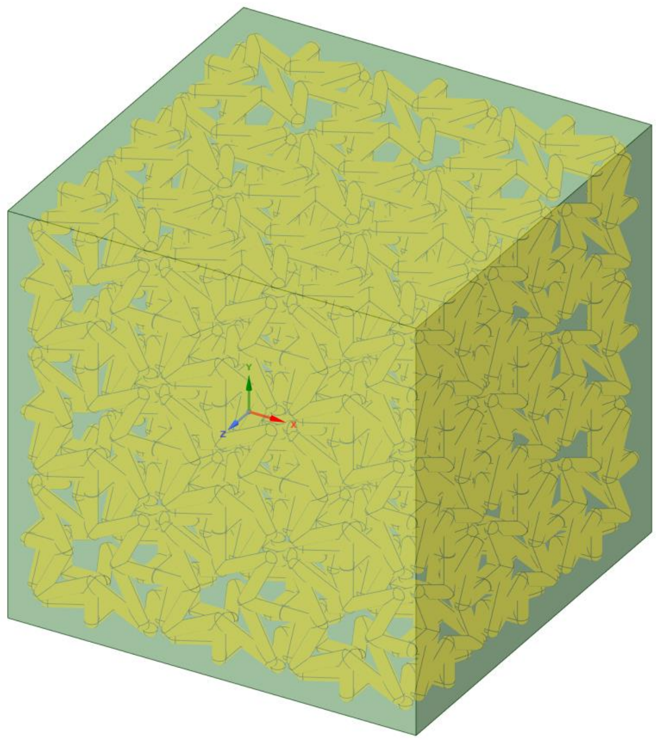

Figure 5C: Composite of 3d re-entrant honeycomb and cubic matrix

This study builds on the foundational work in auxetic materials, which exhibit negative Poisson's ratios and enhanced mechanical properties such as energy absorption and fracture resistance (Alderson & Alderson, 2007; Liu & Hu, 2010). Initial results indicate that both the material properties and geometric parameters of the re-entrant honeycomb significantly affect the composite's stiffness and auxetic behavior, providing valuable insights for designing materials with tailored mechanical properties (Gibson & Ashby, 1997; Lakes, 1987; Bertoldi et al., 2010).

3.2Model parameters

The two most important parameters are used here, one is Material ratio (MR) or Material's young modulus ratio and the other is Volume ratio (VR). Material Ratio (MR) is defined as the ratio of the elastic modulus of the reinforcement fiber material to that of the matrix material Volume Ratio (VR) is defined as the ratio of the volume of reinforcement to the volume of the matrix material. Here consider that 3d re- entrant scaffold have uniform circular cross sections. The scaffold volume Ratio can be controlled by changing the diameter of the scaffold. Because of the limit of the maximum diameter of the scaffold, volume ratio considers from 0.005 to 0.5 for changing volume ratio fiber cross-section diameter (di) varied from 0.1mm to 1mm, respectively (as shown in table 2)

Table 2: Different diameters used for modeling and their corresponding volume ratio (VR).

Parameter	1	2	3	4	5	6	7	8	9	10
Dia	.1 mm	.2 mm	.3 mm	.4 mm	.5 mm	.6 mm	.7 mm	.8 mm	.9 mm	1 mm
VR	.00508	.02035	.04580	.0814	.1272	.1832	.2493	.32572	.4122	.5089

effective poison ratio(PR) and elastic modulus(EM) are depend on the material properties of the both matrix and reinforcement , and there are huge number of verity of material available for using matrix as well as reinforcement so there are multiple combination are possible .So here two cases are taken and observe , in Case-1 use 32 different material ratio(MR) from 1 to 32 by taking 32 different elastic modulus from peek to titanium for the reinforcement material and take matrix material as PEEK only and in Case-2 use 35 different MR from 32 to 1120 by taking reinforcement material as titanium and varies the matrix material's elastic modulus from 3850MPa to 110 MPa with 35 steps (as shown in table 3)

Table 3: Material property used in composite.

Parameter	Case 1	Case 2
young modulus of matrix (E_m)	3500MPa	3500MPa TO 100MPa
Young's modulus of the fiber (E_f)	3500MPa to 18000MPa	18000MPa

It is assumed that the reinforcement fiber and the matrix are made of two different solid materials. Their Young's moduli and Poisson's ratios are denoted as E_f E_m v_f v_m, where subscript f stands for fiber and m represents matrix.

For simplicity and generality, both the Young's moduli of the fiber and the matrix are normalized by that of the matrix, thus the normalized Young's modulus of the matrix is always 1 and the possible range of the normalized Young's modulus of the fiber is given in Table 4

Table 4: Material ratio of fiber and Matrix

Type	Case 1	Case 2
Normalised young modulus of matrix (E_m / E_m)	1	1
normalised Young's modulus of the fiber (E_f / E_m)	1 to 32	32 to 1120

The range of the Young's moduli is from 60 to 400 GPa for most metal, alloys, ceramics and carbon fibers; and from 0.1 to 10GPa for most solid polymers [44] For example, low density Polyethylene has a Young's modulus of 0.15–0.24GPa.

In some 3D printed composites [44], Vero White (rigid photopolymer) is often used as the stiffer phase whose Young's modulus is E_f = 1.66GPa, and Tango Plus (a soft rubbery material) is often used as the softer phase whose Young's modulus is E_m = 0.7456MPa. Thus, the ratio E_f/E_m in such composites is close to 2500. In most polymer, rubber or metal matrix composites reinforced by a metal or ceramic, the ratio E_f/E_m stays in the range from 2 to 1000, In order to enhance the auxetic behaviour (i.e., a large negative Poisson's ratio), a relatively high value of E_f/E_m is desired.

3.3 Computational method

The representative volume element (RVE) Model(Figure 5) of composite reinforced by Auxetic fiber network are constructed using the ANSYS software and all plane or face of the unit cell are symmetric all six faces of the RVE scaffold are made of 2d re-entrant honeycomb. As composite may made of large number of identical representative volume elements (RVEs),but their elastic properties can be obtain from single RVE model and here elastic properties and poisons ratio examine by 4x4x4 cubic model(Figure 6) that is total 64 RVE element are taken and examine the result .Matrix model are very simple in design it is just a simple cube , dimension of the cube are taken as the same of 64 RVE scaffold's.

Both the fiber and matrix materials are assumed to be homogeneous and isotropic solids. In the cubic model Fixed Boundary conditions are applied to three consecutive planes and a small compressive load are applied to one of remaining planes and other 2 plane are free for finite element simulation. Similar to this (Linyi et al., 2023) presents a 3D star-shaped negative Poisson's ratio cell and composite structure, inspired by octagon-shaped 2D negative Poisson's ratio cells. The study found that the size of the cell structure affects the equivalent elastic modulus and Poisson's ratio, with rubber exhibiting the best effect.

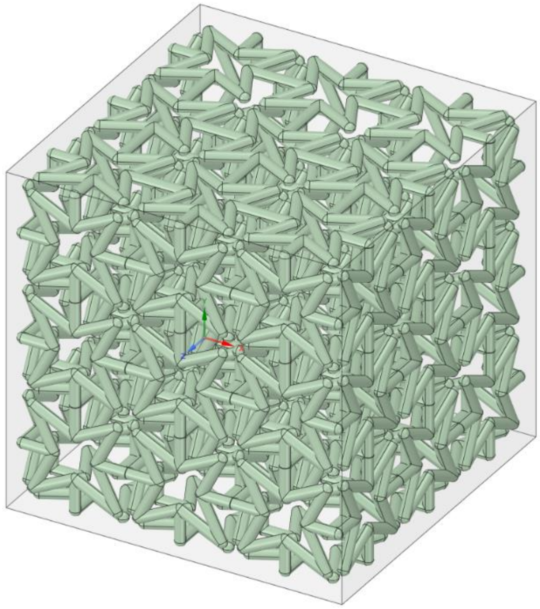

Figure 6: 4x4x4 cubic auxetic model

Chapter 4

Results and Discussions

4 Results

The focus of this study is the negative or zero Poisson's ratio and high elastic modulus. The composite has cubic symmetry in their geometric structure, they have only three independent elastic constants and their elastic properties nearly isotropic, e.g., their Poisson's ratios are the same in their three orthogonal planes. Based on the analysis the below sections can be used as results and discussion for the present study.

4.1. Impact of Volume Ratio on the Poisson's ratio of the composites

The Poisson's ratio of the composite strongly depends on the fiber volume ratio (VR). When the matrix and fiber materials are fixed, the dependence of the Poisson's ratio on the fiber volume ratio can be observed for 10 different VR values.

Figure 7a shows the effect of the fiber volume ratio on the Poisson's ratio for Case 1. As the fiber volume ratio increases, the Poisson's ratio approaches zero from 0.3. This observation is made for a material ratio (MR) of 32, where the reinforcement fiber has a significantly higher elastic modulus compared to the matrix. In this scenario, the negative Poisson's ratio effect of the reinforcement fiber is dominant, but the matrix's positive Poisson's ratio effect is still present. Consequently, the combined effect remains positive or close to zero.

In Figure 7b, the effect of the fiber volume ratio on the Poisson's ratio for Case 2 is shown. Here, the material ratio is 1120, with the reinforcement material being Titanium. The Poisson's ratio varies from -0.2 to -0.3 as the volume ratio increases. In Case 2, due to the very high material ratio, the elastic modulus of the matrix becomes significantly lower, and its positive Poisson's ratio effect nearly vanishes. Thus, the negative Poisson's ratio of the titanium scaffold dominates in this case

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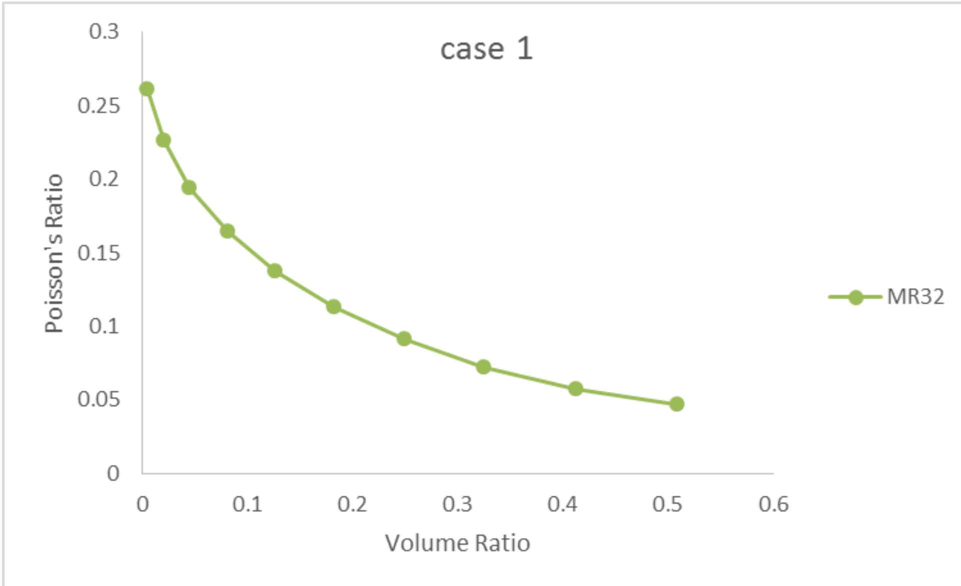

Figure 7a Effect of the fiber volume ratio on the Poisson's ratio for case 1

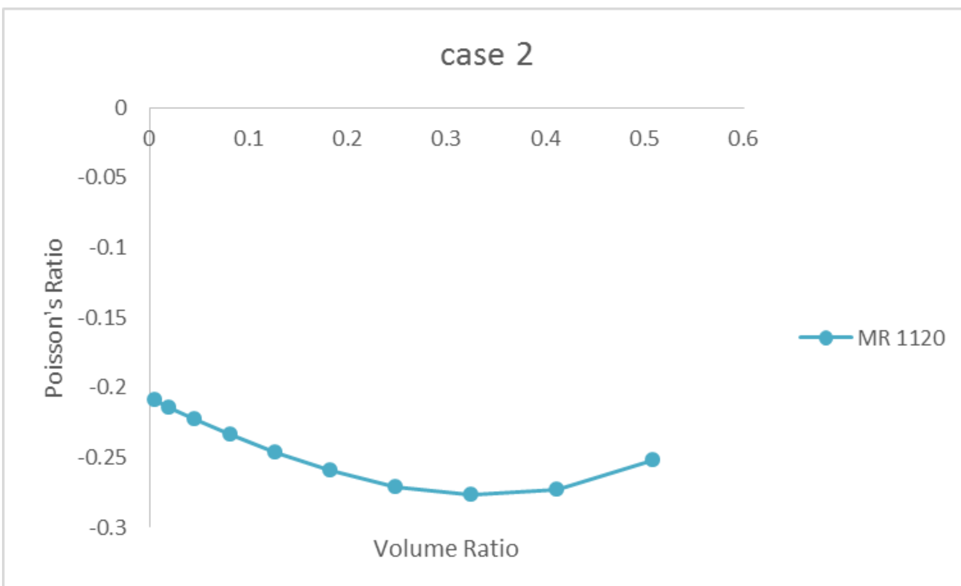

Figure 7b Effect of the fiber volume ratio on the Poisson's ratio for case 2

Effect of Material Ratio on the relationship between fiber volume ratio and Poisson's ratio of the composite

As shown previously, the relationship between volume ratio (VR) and Poisson's ratio (PR) is examined for a single material ratio. Figure 7c illustrates the effect of the material ratio on the VR-PR relationship. For case 1, five different material ratios are considered: (i) Ef/Em=2, (ii) Ef/Em=8, (iii) Ef/Em=15, (iv) Ef/Em=25, and (v) Ef/Em=32. It is clearly shown in Figure 7c that as the material ratio increases, Poisson's ratio approaches zero but remains positive. When the stiffness contrast between the two materials is low to moderate, the composite material behaves more homogeneously. The softer matrix material (Em) and the stiffer inclusion material (Ef) work together to maintain a positive Poisson's ratio, which reflects the typical behavior of most materials where lateral expansion occurs when compressed.

In case 2, illustrated in Figure 7d, the effect of the material ratio on the VR-PR relationship is shown for five different material ratios: (i) Ef/Em=35, (ii) Ef/Em=56, (iii) Ef/Em=112, (iv) Ef/Em=560, and (v) Ef/Em=1120. This figure demonstrates that for material ratios of 35 and 56, Poisson's ratio remains positive. For a material ratio of 112, it shows the transition of Poisson's ratio from positive to negative as the volume ratio changes from 0.05 to 0.5. This suggests that the stiffness of the inclusions is sufficient to alter the overall deformation mechanism of the composite, causing the matrix material to be pulled inwards rather than expanding laterally.

For higher material ratios, Poisson's ratio becomes negative for any value of the volume ratio. As the stiffness contrast increases significantly, the stiffer inclusions dominate the mechanical response of the composite. The matrix material is unable to deform easily to accommodate the stiffer inclusions, leading to complex internal stress states that can cause the Poisson's ratio to shift from positive to negative, particularly at higher volume ratios of the stiff phase.

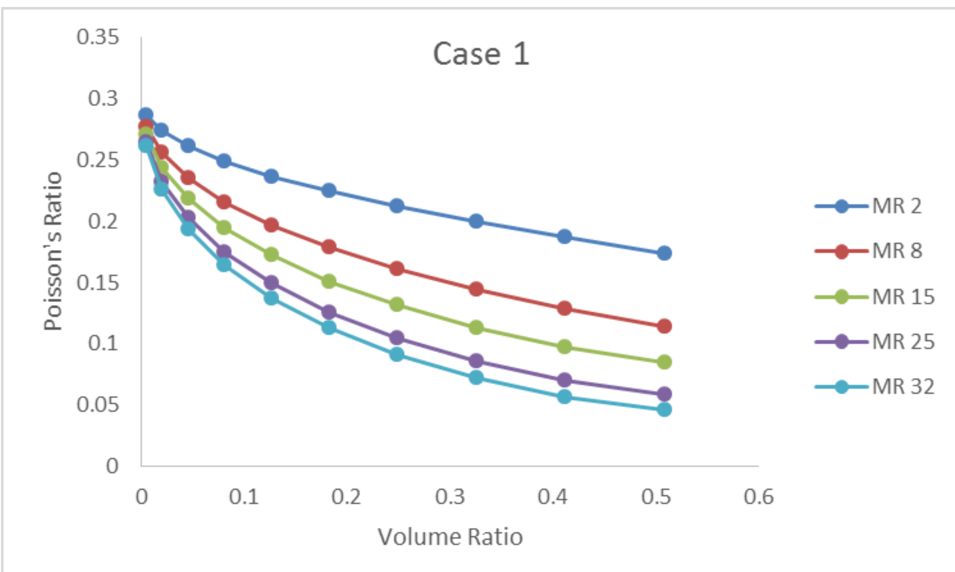

Figure 7c Effect of Material Ratio on the relationship between fiber volume ratio and Poisson’s ratio of the composite for case 1

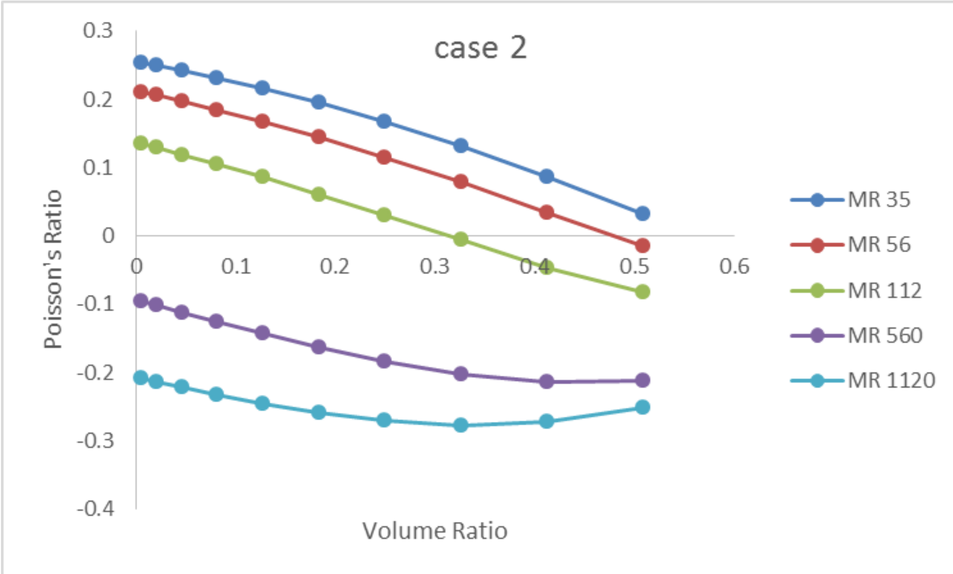

Figure 7d Effect of Material Ratio on the relationship between fiber volume ratio and Poisson's ratio of the composite for case 2.

4.2 Impact of Volume Ratio on the effective young modulus of the composites

The effective Young's modulus of a composite strongly depends on the fiber volume fraction. When the matrix and fiber materials are fixed, Figure 8a shows how the effective Young's modulus increases as the fiber volume ratio increases for case 1 with a material ratio (Ef/Em) of 2. Due to the small increase in the stiffness of the reinforcement material, the composite's effective Young's modulus increases only slightly.

In Figure 8b, case 2 illustrates the changes in the effective Young's modulus for a material ratio of 1120 as the volume ratio changes. For a large material ratio, the change in the effective Young's modulus is very pronounced. This is because, at a material ratio of 1120, the matrix material is significantly less stiff. At a low volume ratio of 0.05, the effective Young's modulus is dominated by the lower stiffness of the matrix material. However, at a higher volume ratio of 0.5, the effective Young's modulus is dominated by the much stiffer fiber material.

This behavior can be explained by considering the significant disparity in stiffness between the fiber and matrix materials. At low fiber volume fractions, the matrix largely governs the mechanical properties of the composite. As the fiber volume fraction increases, the stiffer fibers contribute more significantly to the composite's overall stiffness, leading to a substantial increase in the effective Young's modulus, especially noticeable when the stiffness contrast between the fiber and matrix is extremely high.

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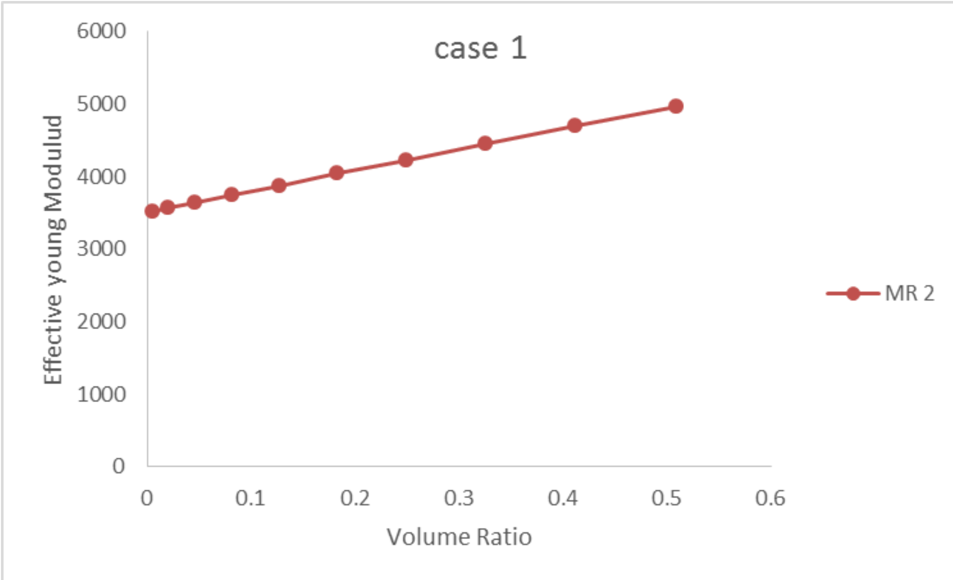

Figure 8a Effect of the fiber volume ratio on the effective young modulus for case 1

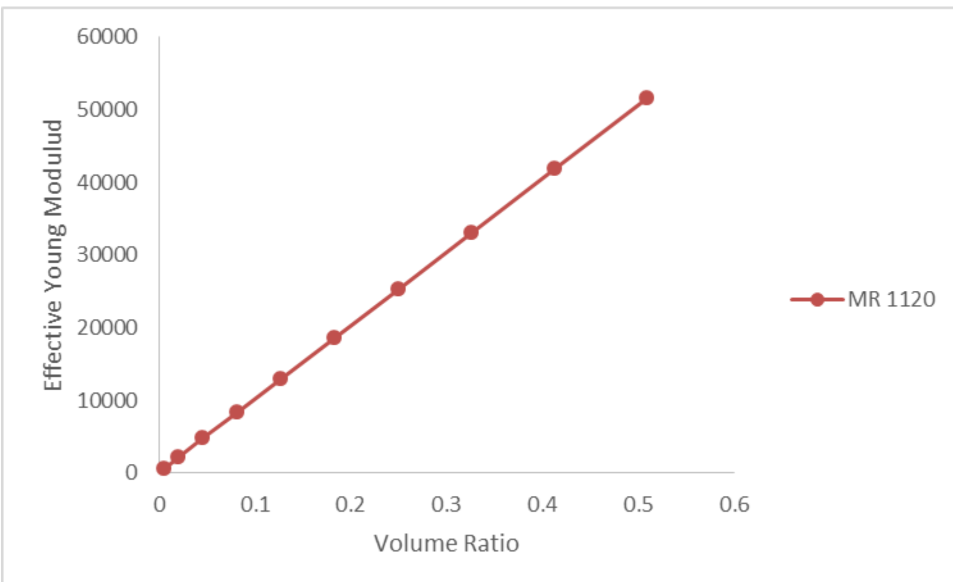

Figure 8b Effect of the fiber volume ratio on the effective young modulus for case 2

Effect of Material Ratio on the relationship between Effective young modulus and Poisson's ratio of the composite

Figure 8c shows the effect of material ratio on the relationship between Volume Ratio and Effective Young Modulus. In case 1 there are 32 different material ratio and take only 5 those are (i) $E_f/E_m=2$ (ii) $E_f/E_m=10$ (iii) $E_f/E_m=20$ (iv) $E_f/E_m=30$ and it clearly shows that for material ratio 2 the change of effective young modulus is very less as compare to when the material ratio is 32.

For case 2 there are 35 different material ratios but take only four different MR or E_f/E_m are (i) E_f/E_m=35 (ii) E_f/E_m=70 (iii) E_f/E_m=112 (iv) E_f/E_m=1120. In figure 8d shows that effects of material ratio on effective young modulus are very minor (as shown in figure 8e).

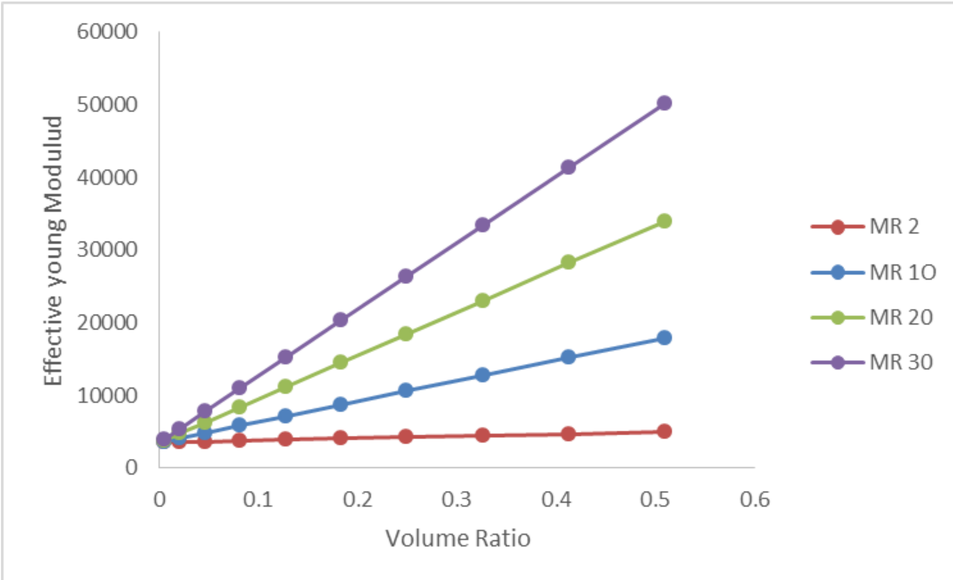

Figure 8c Effect of Material Ratio on the relationship between Effective young modulud and Poisson's ratio of the composite for case 1.

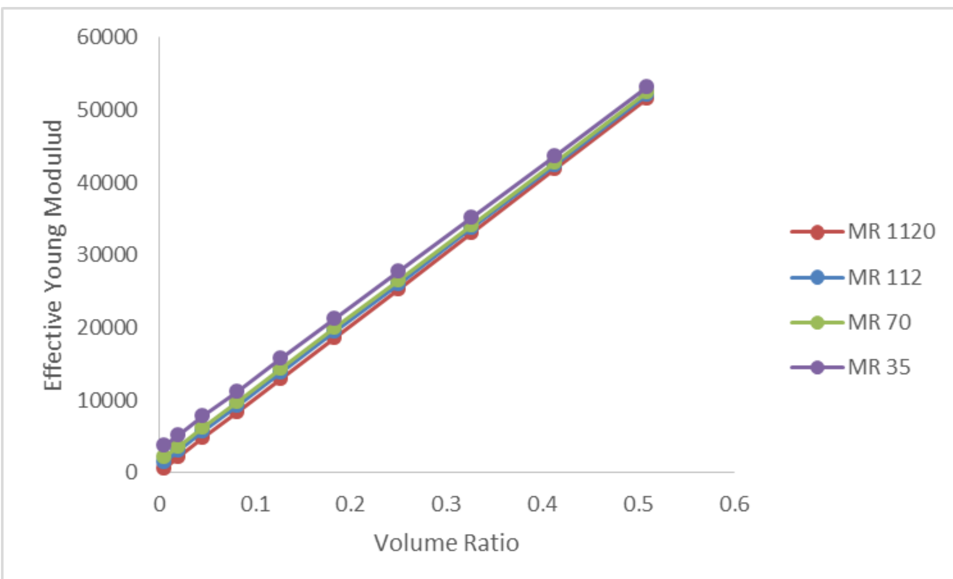

Figure 8d Effect of Material Ratio on the relationship between Effective young modulus and Poisson's ratio of the composite for case 2.

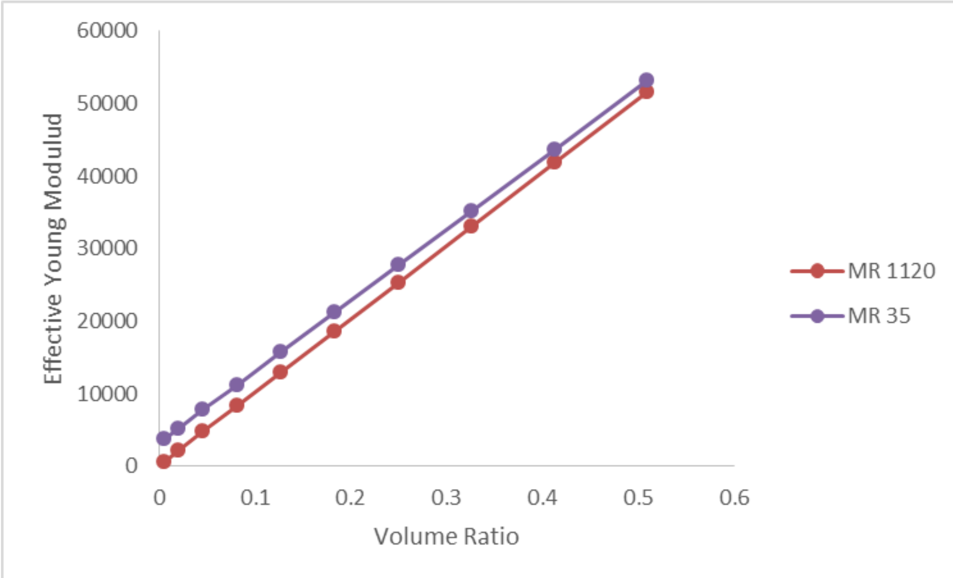

Figure 8e Effect of Material Ratio on the relationship between Effective young modulus and Poisson's ratio of the composite for case 2

4.3 Effects of Material Ratio on the Poisson's ratio of the composites

for maximum volume ratio 0.5 for case 1 In figure 9a shows the relation between material ratio and Poisson's ratio, for increasing material ratio the reinforcement fiber will stiffer that's why the Poisson's ratio of the composite is reduce from .3 to near zero. and for case 2 increasing in material ratio means the effect of the matrix will reduce that's why the resulting Poisson's ratio of the composite is dominating by the fiber, and the auxetic behavior shown in figure 9b.

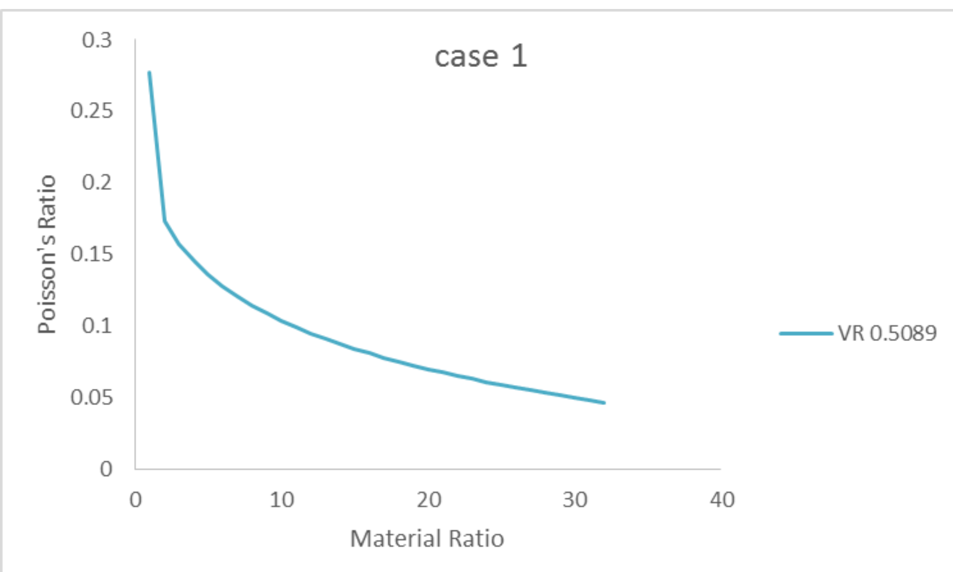

Figure 9a Effect of Material Ratio on the Poisson's ratio of the composite for case 1

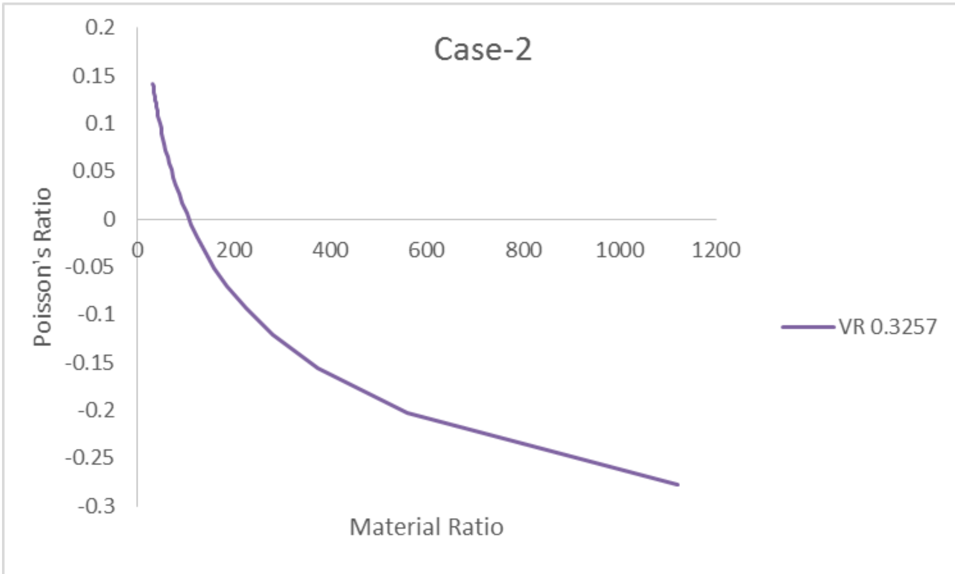

Figure 9b Effect of Material Ratio on the Poisson's ratio of the composite for case 2

For each case there are 10 different Volume Ratio present but only 5 different Volume Ratio are taken, those are (i)VR=0.02 (ii) VR=0.08 (iii) VR=0.18 (iv) VR=0.32 (v) VR=0.50. In figure 9c and figure 9d for case 1 and case 2, respectively shows the effect of volume ratio on relationship between MR vs PR.

It can be observed that as the ratio Ef/Em increases, the more obvious auxetic behaviour the composites exhibit. With the reduction of the Ef/Em, the auxetic behaviour of the composites gradually disappears. This is because the self-connected auxetic fiber-network with a larger value of Ef/Em can more strongly dominate the auxetic behaviour of the composites.

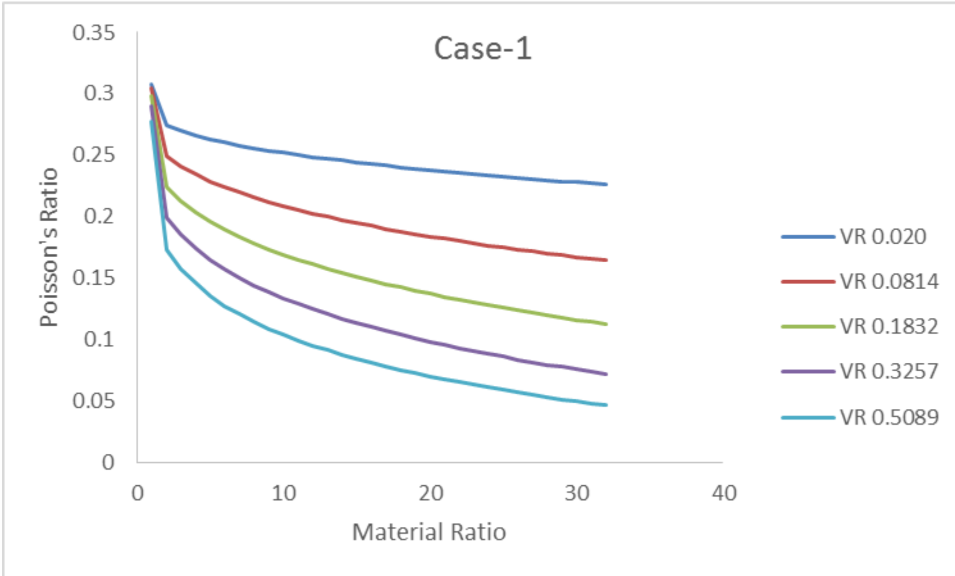

Figure 9c Effect of Volume Ratio on the relationship between Material Ratio and Poisson's ratio of the composite for case 1

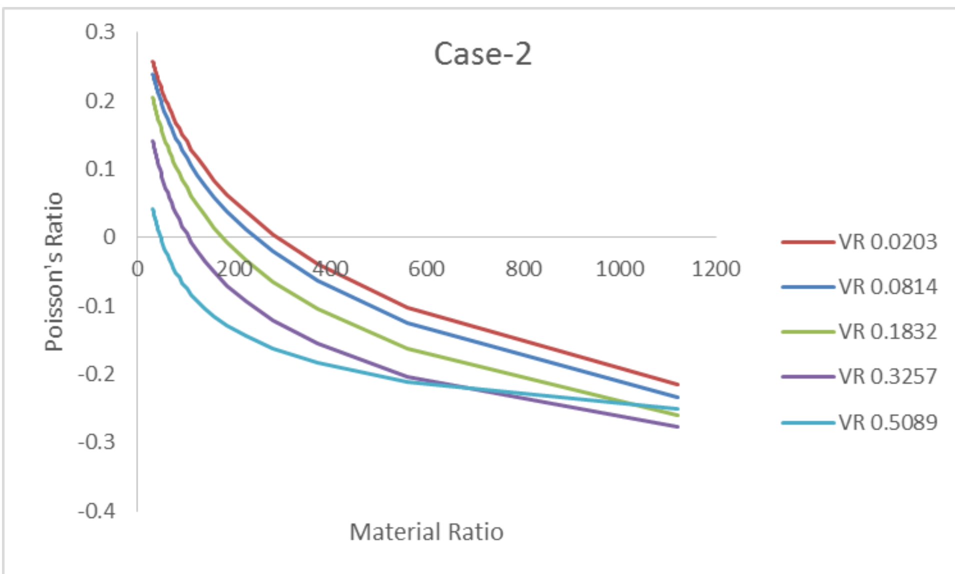

Figure 9d Effect of Volume Ratio on the relationship between Material Ratio and Poisson's ratio of the composite for case 2

4.4 Effects of Material Ratio on the effective young modulus ratio of the composites

With a constant volume ratio 0.32 for case 1 and case 2 shows the relation between material ratio and effective young modulus in figure 10a and figure 10b respectively. for case 1 as the matrix material fixed and fiber material's elasticity increase while the material ratio increases that's why the effective young modulus are increase.

For case 2 fiber material is fixed and for increasing the material ratio uses lesser elastic material for matrix and that's why the combine effect composite will decrease. And after the value material ratio 500 the effect of matrix will very less so the effective young modulus is almost constant after that range.

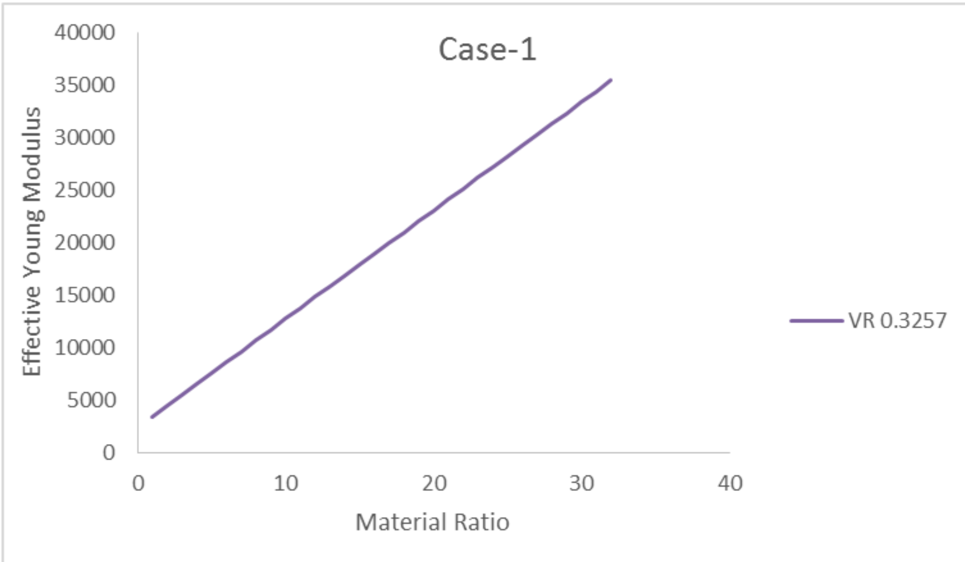

Figure 10a Effect of material ratio on the Effective Young modulus of the composite for case 1

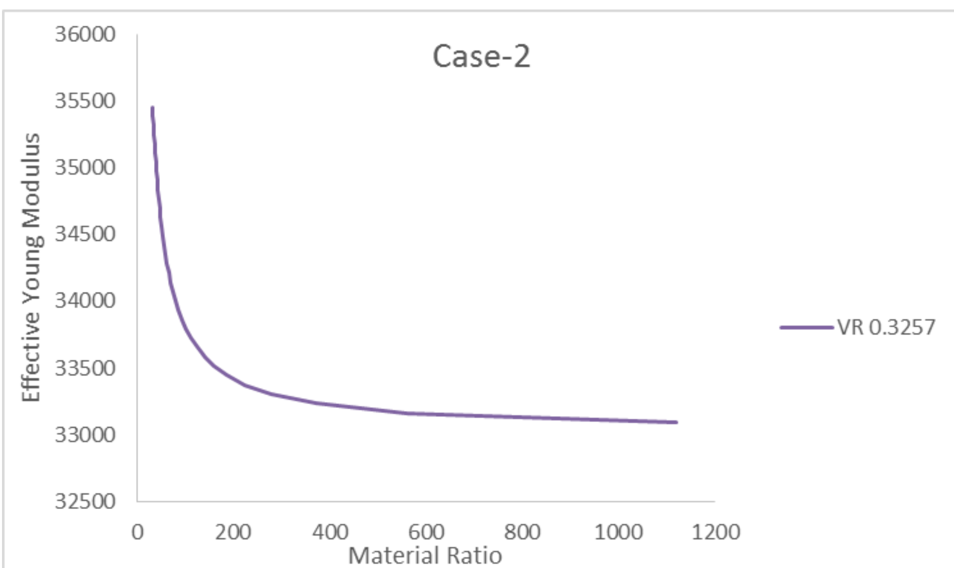

Figure 10b Effect of material ratio on the Effective Young modulus of the composite for case 2

Effect of volume ratio on the relation between material ratio and effective young modulus are shown in figure 10c and figure 10d for case 1 and case 2 respectively. Five different fiber volume ratio those are (i)VR=0.02 (ii) VR=0.08 (iii) VR=0.18 (iv) VR=0.32 (v) VR=0.50.

In both case the fiber material shows the major role on effective young modulus that's why the effective young modulus will increase in the increasing the volume ratio of the fiber.

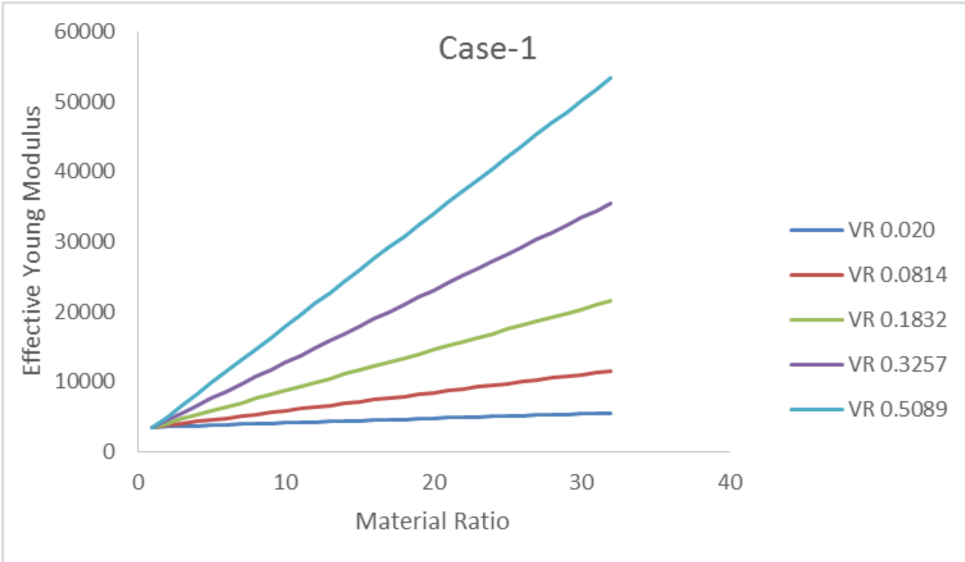

Figure 10c Effect of Volume Ratio on the relationship between Material Ratio and Effective young modulus of the composite for case 1

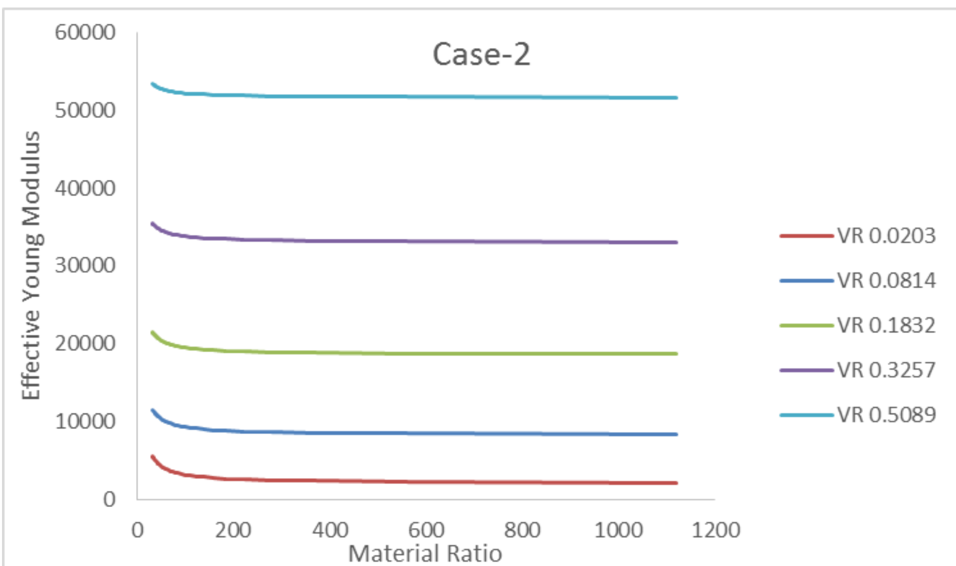

Figure 10d Effect of Volume Ratio on the relationship between Material Ratio and Effective young modulus of the composite for case 2

4.5 The relationship of the Poisson’s ratio with volume ratio and Material ratio.

The effect of Ef/Em and volume ratio on Poisson’s ratio are shown in figure 11a and figure 11b for case 1 and case 2 respectively.

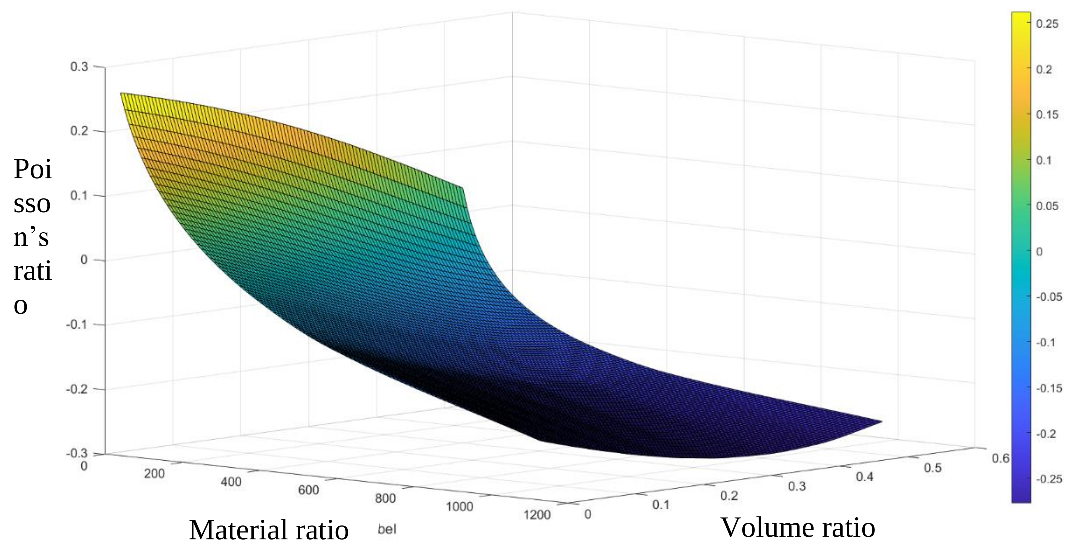

Figure 11a Combine the effect of fiber Volume Ratio and Material ratio on the Poisson’s ratio of the composite for case 1.

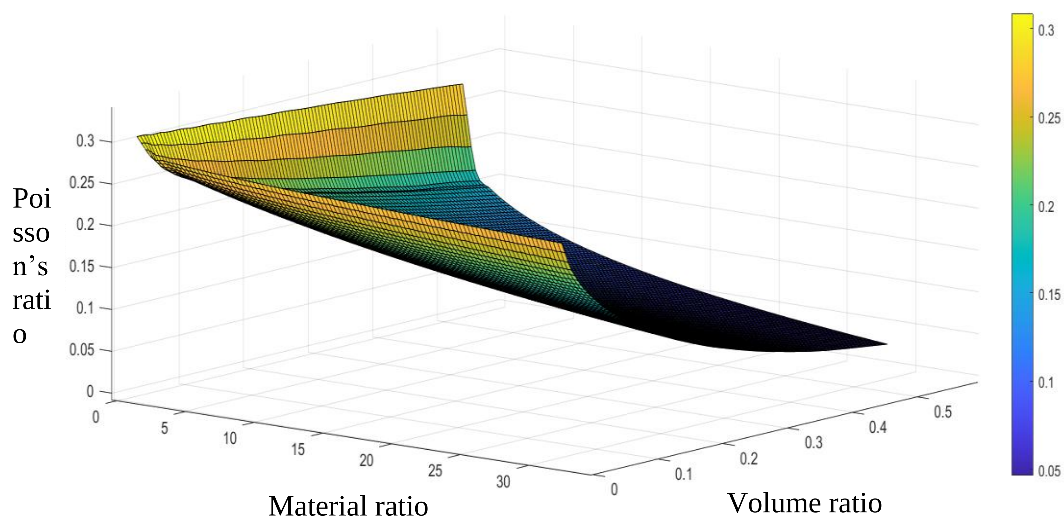

Figure 11b Combine the effect of fiber Volume Ratio and Material ratio on the Poisson’s ratio of the composite for case 2.

4.6 The relationship of effective elastic modulus with fiber volume ratio and material ratio of the composite.

The effect of Ef/Em and volume ratio on effective young modulus shows in figure 12a and figure 12b for case 1 for case 2 respectively.

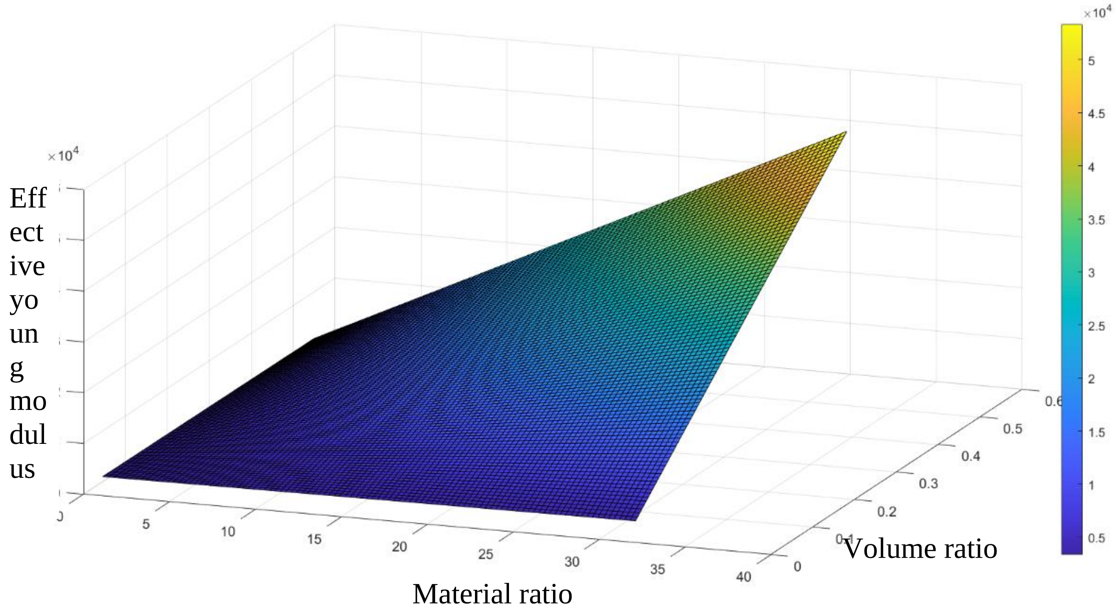

Figure 12a combine effect of fiber volume ratio and material ratio on the effective elastic modulus of the composite for case 1

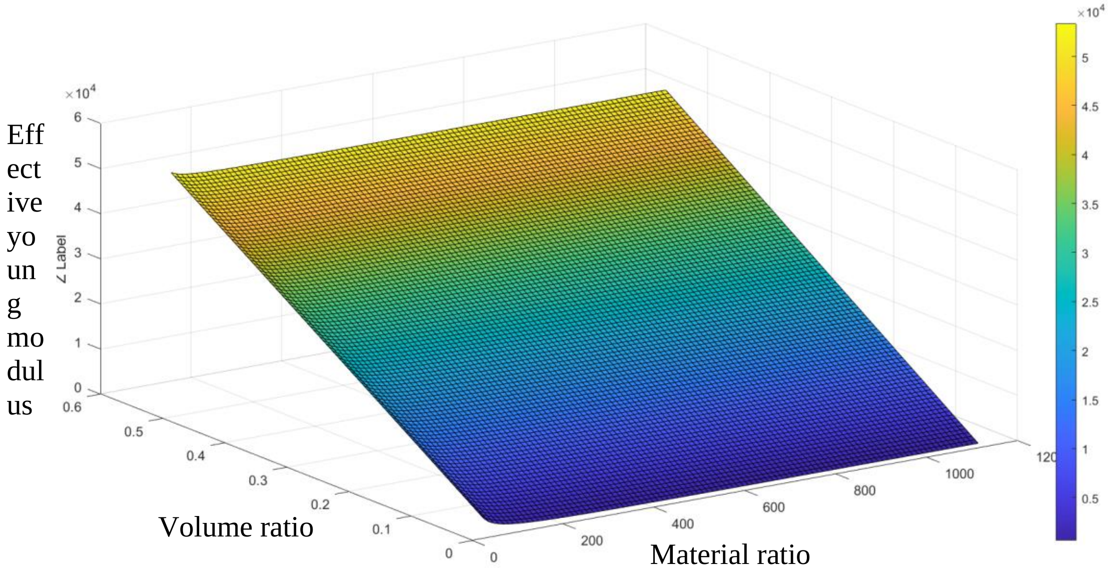

Figure 12b combine effect of fiber volume ratio and material ratio on the effective elastic modulus of the composite for case 2.

Chapter 5

Conclusions and Future Scope

5.1 Conclusions

This study explored the interesting world of negative Poisson's ratio in composite materials. By using a 3D re-entrant auxetic cube and varying the fiber volume fraction across ten different ratios, we examined a total of sixty-seven material combinations. The key conclusions from this work are:

a) Unlike common materials with negative Poisson's ratios, which are usually porous or very directional, this study focuses on solid composites with different auxetic fiber networks. These composites can have positive, negative, or zero Poisson's ratios depending on the fiber network structure, fiber volume fraction, and the mechanical properties of the materials used (Ef/Em, νf, and νm).

b) These composites, which do not have pores and are strengthened by a self-connected fiber network, have Young's moduli that are higher than those of traditional particle composites. Additionally, their cubic symmetry makes their mechanical properties nearly the same in all directions. The structural hierarchy also significantly enhances their auxetic behavior.

c) The findings highlight the functional capabilities of auxetic interpenetrating composites and their potential use as structural materials in various engineering applications.

5.2 Future Scope of work

The present work can be extended for further studies. The future direction can be such as.

a) Future research can try other combinations of biomaterials to further enhance or change the auxetic properties of the composite. Testing different materials could lead to composites with better performance for specific uses

b) While the current composite is non-porous, future studies could explore adding controlled porosity. Porous structures could be useful in medical fields like tissue engineering, where the movement of nutrients and cells is important.

c) Future research can use advanced computer techniques and simulations to predict how the composite behaves under various conditions. Using methods like machine learning and finite element analysis (FEA) can give more detailed insights into how the composite handles stress and strain and what might cause it to fail.

d) The theoretical results from this study should be validated through experiments. Future research should aim to make the composite and test it mechanically to compare real-world data with predictions.

e) For medical applications, it's crucial to study how the composite interacts with biological tissues. Future research can focus on testing the composite in the lab and in living organisms to see how safe and effective it is for medical use.

f) Future studies can tailor the composite for specific uses, like bone implants, prosthetics, or soft tissue repair. Adjusting the material properties to meet the needs of different medical conditions or individual patients can make the composite more useful.

g) Research should look into how well the composite holds up over time. Studying its long-term durability and performance will help understand how it behaves in real-world conditions and ensure its reliability.

h) Exploring the environmental and economic impact of producing and using these composites is important. Future research can focus on making the production process more sustainable and cost-effective, which will help in large-scale adoption and implementation.

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