

EFFECT OF MATERIAL EXTRUSION PARAMETERS ON THE MECHANICAL PERFORMANCE OF AUXETIC CELLULAR STRUCTURES

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ABSTRACT

The growing demand for lightweight, high-performance materials has led to increased interest in auxetic cellular structures, which exhibit a negative Poisson's ratio and unique deformation behavior. This study investigates the mechanical performance of 3D printed auxetic cellular structures fabricated using material extrusion techniques, commonly known as fused deposition modeling (FDM). Auxetic geometries, such as re-entrant honeycomb and chiral structures, were designed and manufactured using thermoplastic materials to evaluate their structural response under various loading conditions. The research focuses on analyzing key mechanical properties, including compressive strength, stiffness, energy absorption, and deformation characteristics. Specimens were fabricated with varying printing parameters such as layer height, infill density, and printing orientation to assess their influence on mechanical performance. Experimental testing was conducted using universal testing machines, and the results were compared with numerical simulations to validate the behavior of the auxetic designs. The findings demonstrate that auxetic structures exhibit enhanced energy absorption capacity and improved resistance to deformation compared to conventional cellular structures. Additionally, the study highlights the critical role of material extrusion parameters in determining structural integrity and mechanical efficiency. The optimized auxetic designs show potential for applications in impact protection, biomedical implants, aerospace components, and flexible engineering systems. This research contributes to the understanding of the relationship between design geometry, manufacturing parameters, and mechanical performance of 3D printed auxetic structures, providing a foundation for future advancements in additive manufacturing and smart material design.

Keywords: auxetic cellular structures, mechanical performance, material extrusion techniques, auxetic designs

INTRODUCTION

Different geometric parameters of auxetic cellular structure, including single-cell dimensions, overall dimensions of the structure, angle between cell components, structure thickness, the various geometric ratio of components, and porosity on the structure, will be measured and evaluated using numerical modeling and analytical relations. Then, using sensitivity analysis, each parameter's impact on the Poisson's ratio and the elastic modulus is represented. The goal is to see the effect of each of the different parameters of the cell on the Poisson's ratio and the elastic modulus that affect the mechanical behavior of the structure. On the basis of this analysis, a structural design with unique features is provided to demonstrate its application. The Poisson's ratio of the material is the ratio of transverse strain to longitudinal strain in the loading direction. Materials that have a negative Poisson's ratio, unlike conventional materials, become thicker under stretch and thinner under pressure, which is called auxetic material. Auxetic materials are made up of small geometric units called cellular units whose auxetic effects are caused by these cells. In isotropic materials, their properties such as modulus of elasticity and Poisson's ratio are

similar but in anisotropic materials, these properties are varying in different directions. The Poisson's ratio boundaries of three-dimensional isotropic elastic body is between -1 and 0.5 . Spectacular changes of Poisson's ratio occur in anisotropic auxetic materials outside the isotropic range. With the advancement and development of the auxetic structure, these materials have gone beyond the range of isotropic and macro-scale materials and have expanded from both the isotropic and anisotropic material categories from macro to nano scales. Many materials, such as cat skin, cow skin, and sponge bone, naturally have auxetic properties lying within them. During the past few decades, due to developments in the design, technology and engineering of industries, such as aerospace, military, and sports industries, has demanded new materials with higher engineering specifications. Less well-known cellular structures, known as auxetic structures, undergo lateral expansion in response to tension and contraction in response to compression. Because of their unusual behaviour, they are being considered as potential materials for use in biomedical applications, lightweight engineering, compression endurance impact-resistant armours, and cars. There are several variations of these structures; some relevant examples are re-entrant, honeycomb, chiral, and gyroid. Such intricate constructions have recently been physically possible thanks to numerically controlled technology. More and more people are looking to 3D-printed technologies to build these kinds of constructions these days. Limitations in both resources and budget dictate which printing method is ultimately chosen. As a

manufacturing technology, fused deposition modelling (FDM) has seen widespread use for polymer-based structures due to its cheap cost and simplicity of adaption. When anisotropy is present in a material or system, its qualities change depending on the direction of measurement. Problems in printing specific complicated geometries and less-than-ideal mechanical characteristics and bonding between interlayer-printed materials were outcomes of AM's layer-by-layer manufacturing technique.

LITERATURE REVIEW

Aman Garg (2025) An interesting aspect of auxetic structures is that they contract in all directions when compressed and expand in all directions under tensile strain. These structures are defined by a negative Poisson's ratio. How the material is organised inside the unit cell and how the cells interact with one other greatly affect the behaviour of these structures. Understanding and simulating auxetic materials is very challenging and calls for sophisticated modelling frameworks and a lot of experimentation because of how complicated their behaviour is. Consequently, ML approaches have become an effective tool for analysing the behaviour of auxetic metamaterials under different loading circumstances and for predicting their mechanical characteristics. In order to forecast the qualities and functionality of auxetic metamaterials, this article offers a thorough examination of the use of ML algorithms. It goes into depth on the datasets, methods, 3D printing technology used to make samples, and auxetic structural geometries that have been studied in the literature. Included in this study are both 3D-printed structures and

results from models based on finite elements.

Yulong Wang (2024) Auxetic lattice structures, in particular, have emerged as a result of additive manufacturing (AM) technology. These multifunctional units have a remarkably repeating three-dimensional pattern. Lightweight, high-performance components using these architectures could improve efficiency, which might have aerospace applications. This article delves into the design, numerical modelling, manufacturing, and testing of three-dimensional star-shaped lattice structures that have adjustable mechanical properties. The Poisson's ratio and effective elastic modulus of the lattice structure were studied using finite element analysis (FEA) in relation to the vertex angle and strut diameter. The vertex angle was adjusted from fifteen degrees to ninety degrees, and the strut diameter was changed from two and a half millimetres to one millimetre across a star pattern. After verification of the models' correctness by compression testing, experimental fabrication of 3D star-shaped honeycomb structures using the AM technique of laser powder bed fusion (LPBF) was carried out.

Peiqing Liu (2023) Auxetic structures have negative Poisson's ratios (NPR). Thanks to their one-of-a-kind deformation mechanism, auxetic structures exhibit remarkable mechanical properties including energy absorption capacity, fracture toughness, indentation resistance, and shear resistance. However, the stiffness and load-bearing capabilities of auxetic structures are their weak points. 3D printing continuous fiber-reinforced composite enables the development of complex structures that are both lightweight and very

stiff, making it a suitable manufacturing solution to overcome the disadvantages of auxetic structures. Using 3D-printed continuous fiber-reinforced composite, this research analysed the mechanical properties of auxetic structures. For this research, we 3D printed two different auxetic structures using continuous fiber-reinforced composite material. To investigate how different fibre distributions affected mechanical qualities, test specimens had different fibre route layouts. Auxetic constructions reinforced with continuous fibres were subjected to a uniaxial tensile test to measure their tensile strength and Poisson's ratio. With just a little increase in mass, the results demonstrated a remarkable improvement in both the tensile modulus and strength. By distributing the reinforcing fibres correctly, the auxetic behaviour may be enhanced. The specified auxetic structures showed differing performances once continuous fibre was added.

Gonzalo Pincheira (2022) This work proposes a three-dimensional auxetic structure that incorporates a design parameter that produces asymmetry, based on a known planar arrangement. To achieve the necessary orthotropic elastic characteristics, the auxetic cell is constructed using topology analysis with conventional Timoshenko beam theory. The structure's Poisson's ratio and Young's modulus are statistically determined by fabricating samples using the ABSplus fused filament process and then testing them under quasi-static compression. In line with the topological analysis, the experimental findings demonstrate that the suggested structure may successfully provide distinct elastic characteristics along

its three orthogonal axes. Furthermore, the mechanical behaviour of this cellular structure was determined by conducting three point bending experiments. The findings reveal that this auxetic cell affects the macrostructure in three distinct ways, each of which affects the stiffness behaviour. Topics covered include cellular structure, auxetic structures, and additive manufacturing.

Sohail Gohar (2021) The auxetic structures' remarkable mechanical qualities under bending, shear, and compression stresses make them very applicable in the aerospace and automotive industries, where their negative Poisson's ratio is a key characteristic. Three new auxetic structures were developed in this work by modifying previously published ones. The innovative structures' in-plane mechanical performance under uniaxial compression loads was assessed with the use of finite element analysis (FEA) models that had been verified experimentally. We also looked at how they behaved when deformed and when they collapsed. When compared to the standard re-entrant structure, all of the novel auxetic structures showed improved energy absorption capabilities and a higher Young's modulus. The conventional and novel structures were subjected to a topology optimisation approach called shape optimisation in order to further improve their attributes listed above. This technique has not been investigated for its impact on the mechanical performance of auxetic structures.

Dynamic Auxetic Structure Design Based on Simulations

The symmetry and mechanical performance of a tetra-petal star-shaped

unit cell were taken into consideration while choosing this pattern for the design and examination in this work from among the many auxetic designs previously investigated in the literature. A hinge and elastic support system, similar to that of star-shaped structures, explains the auxetic reaction of petal structures. Compared to older production techniques, this one is better since sharp edges no longer lead to stress concentrations and discontinuities. Furthermore, tetra-petal structures exhibit a greater auxetic response compared to tri- or hexa-petal structures; nevertheless, the specifics of this behaviour are highly influenced by the dimensions, contours, and geometrical characteristics of the petals. Several geometrical elements of the cells were adjusted during the numerical parameter analysis, including the petals' and interpetals' angles, the base strut's distance from the center, the petals' radius, and the struts' thickness, once the unit cell shape was selected. The objective was to determine the minimum Poisson's ratio that the tetra-petal unit cells might exhibit when subjected to compression stresses.

Auxetic Materials

Presented in this chapter is an overview of the auxetic materials. We begin our examination of these materials with a definition based on Poisson's ratio and a synopsis of auxetics's past. Based on their production, auxetic materials are categorised and their structures are described. Here are the key characteristics of auxetic materials along with a comparison to "normal" materials to help you better understand how they behave. The article concludes with a variety of field uses that auxetic materials have. The Poisson's ratio is a constant that does not

have dimensions; it is directionally dependent on the applied load and defines the negative transverse strain to longitudinal strain ratio of a body subjected to a tensile force. Comparing the structural performance of actual homogeneous and non-homogeneous materials is what it's all about. The implicit assumption that Poisson's ratio is positive stems from the long-held belief that isotropic materials in nature cannot have a negative value. Still, there are materials whose behaviour is the exact opposite. This material has a negative Poisson's ratio because it enlarges in the transverse direction under axial tensile stress and contracts in the compression direction.

Prospect of Auxetic Structures

The theory and modelling of auxetic structures have been the subject of extensive investigation for quite some time. Muscles, ligaments, vascular, skin, and bone tissues are all made of tissues having a negative Poisson's ratio, as has been shown in recent years via extensive study on the human body. So, researchers in the field of tissue engineering are looking at auxetic structures as potential replacements for these tissues. For medical devices including bio-prostheses, stents, hip stems, and surgical screws, auxetic structures were used and used more widely because of their increased compressive strength and shear stiffness. Biomaterials have several restrictions about their usage in humans at the moment. Hence, structural design must be used to find mechanical qualities that are compatible with natural tissues, barring the development of novel and biocompatible materials. When faced with such constraints, auxetic structures endowed with adjustable features are seen as a potent

instrument for repurposing scarce biomaterials for physiological applications. Furthermore, in contrast to chemical therapy, they were quite safe in vivo as they only altered the interior structure physically.

Cellular structures and density grading

Architected materials have been in the spotlight recently because of their unusual and adjustable mechanical qualities, which set them apart from both naturally occurring and traditionally manufactured materials. The remarkable attributes of these materials are a result of their well planned internal structures, which allow for the enhancement of qualities like strength, rigidity, and energy absorption. Foams and cellular structures are the two main types of architectural materials. Bones and corals are examples of natural formations that exhibit foams, which are porous materials with densities spread randomly. Cellular structures, on the other hand, are characterised by periodic and programmable geometries, which enable the exact customisation of mechanical characteristics. Optimal design allows for the engineering of periodic 3D cellular structures to exhibit desirable mechanical behaviours, which are the subject of this study. The most notable of these are structures with triply periodic minimum surfaces (TPMS) and strut-based lattices.

METHODOLOGY

This chapter presents experimental study of influence of geometric, process and gradient parameters on mechanical properties of re-entrant auxetic structure under compressive loading. Regression models are developed for prediction of mechanical properties; and optimization of parameters is also performed. This research

takes into account the re-entrant angle, height, and arm-length as three geometric characteristics of the re-entrant auxetic structure. presents the PRISMA flow chart for the systematic review of auxetic structures. This review adopted a systematic review methodology and strictly followed the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) standards to ensure transparency. Mechanical parameters and the deformation behaviour form the foci of our result evaluation, and these parameters were obtained by compression testing. Compression testing was carried out using compression-testing equipment and simulations using the finite element method (FEM). Testing parameters and FEM calculation details are also presented in this section. The expected deformation behaviour and mechanical properties, such as Poisson's ratio, are predicted by a complex analytical approach. A gradation of auxetic structures typically leads to improvements in mechanical properties. additionally illustrates the intermediate stage of the printing simulation of the sandwich geometries. For the dilatometry (DLM) measurements, smaller samples were printed in order to be able to place them in the corresponding device, although the cell sizes were maintained.

RESULTS AND DISCUSSIONS

We can see the outcomes of our experiments with the artificial auxetic structures in Table 1. The stress-strain curves for all configurations show that structures withstand load at first, and subsequently the cell wall begins to collapse. When cells that have collapsed start to condense, structures begin to resist load once again. Until the whole structure is

compressed, the stress levels will rise and fall.

Table 1 Experimental results for auxetic structures

Material	ABS	PLA				
Run no.	Compressive Strength	SEA	Compressive Strength	Compressive Strength	SEA	
	MPa	MPa	J/gm	MPa	MPa	J/gm
1	2.586	85.955	227.867	3.9	107.908	117.321
2	3.106	74.55	462.844	2.68	26.804	137.508
3	2.228	40.439	6924.14	4.102	87.477	2056.39
4	3.671	95.627	338.054	1.257	14.386	101.118
5	2.286	22.863	9749.42	2.058	29.062	2954.17
6	3.42	93.21	320.127	1.279	15.324	83.426
7	2.317	33.407	208.629	3.884	85.139	134.108
8	1.455	29.878	3754.15	4.365	78.729	13030.8
9	2.65	89.43	220.33	4.056	108.124	102.57
10	1.759	37.139	12422.6	2.958	57.856	8512.58
11	1.563	35.124	12340.7	3.124	55.124	8417.28

12	2.217	40.1 24	7012 .5	4.12	86.1 24	2013.7 8
13	2.317	33.1 24	200. 127	3.9	84.0 12	112.78 9
14	3.107	74.1 28	455. 27	2.7	27.1 24	120.15 8
15	2.378	22.1 27	9800 .24	2.09 8	29.0 12	2801.1 3
16	1.4	29.1 2	3600 .13	4.42 7	77.1 28	14014. 6

This deformation behaviour is present in all configurations, with minor variations according to the structure's material and the geometry of the unit cell. The stress-strain curves in Figure 1 show that all three configurations go through the same three phases of deformation: the elastic, plateau, and densification stages. When the strain on the unit cell increases, it enters an elastic deformation mode and then experiences plateau stress. As a result of the bending of inclined cell walls, structures experience elastic-plastic deformation throughout this strain-range. The first collapse of cell walls is caused by further increases in strain. When strain is modest, the stress-strain curves are almost linear, allowing for the calculation of stiffness. Depending on the feedstock material, buckling or brittle fracture may cause the structure to collapse once it reaches the critical strain limit. Collapsing of cell walls occurs when opposing cell walls touch each other under increasing strain.

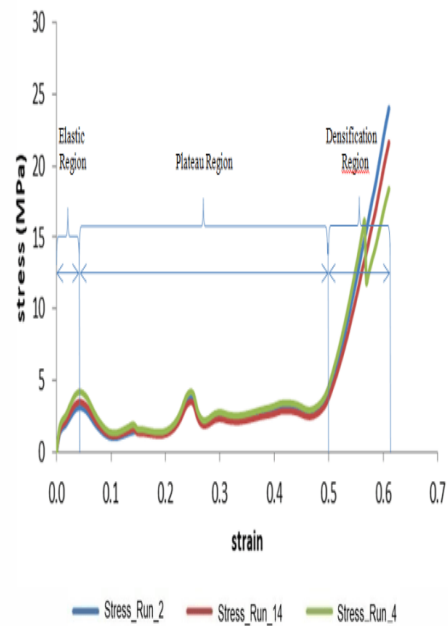


Figure 1 Curve of stress and strain for ABS constructions

According to the results of the analysis of variance (ANOVA), all three geometric characteristics have a substantial impact on compressive strength and stiffness in structures constructed of ABS and PLA, although arm length is the most important element affecting SEA. Table 2 shows the relationship between the responses and the geometric characteristics of the constructions.

There is a strong relationship between re-entrant angle and arm length, between re-entrant angle and height, and between arm length and arm length when it comes to the compressive strength of ABS constructions.

Table 2 Summary of Correlation of response with geometric parameters

Material	ABS	PLA
Is		

Parameters	Compressive strength	Compressive stiffness	SEA	Compressive strength	Compressive stiffness	SEA
Re-entrant angle	Negative	Negative	Positive	Positive	Positive	Positive
Height	Positive	Positive	Negative	Positive	Positive	Positive
Arm-length	Negative	Negative	Positive	Negative	Negative	Positive

CONCLUSION

Auxetic cellular structures created by material extrusion and 3D printing were tested for mechanical performance in this study. Because of their unique deformation processes and negative Poisson's ratio behaviour, auxetic structures are ideal for modern engineering applications such as energy absorption systems, biomedical implants, protective gear, and lightweight structural components. The main goal of this study was to use additive manufacturing to create auxetic cellular structures and then test their mechanical reaction to see how different geometric design and manufacturing factors affected them. Prior to delving into cellular structure design and auxetic geometry, the investigation began. Compared to conventional materials, auxetic structures are quite unique due to their lateral

expansion and contraction capabilities. Not only does this unusual deformation process boost the material's ability to absorb energy, but it also increases its shear resistance and indentation resistance. Notable auxetic geometries that have been described in the literature include re-entrant honeycombs, chiral structures, and spinning unit cells. To assess their compressive behaviour and structural performance, the mechanical testing was performed on the artificial auxetic cellular specimens. This material's energy absorption properties, stiffness, load-bearing capacity, and deformation processes were studied using compression experiments. When contrasted with regular cellular structures, the findings showed that auxetic structures deform in unique ways. As auxetic behaviour was proven, the cell walls were able to rotate and extend laterally under compression thanks to the re-entrant shape.

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