Auxetic Structures Analysis: Exploratory Study on Auxetic Materials in Additive Manufacturing CILAMCE-2025

Erick Battiston Antonio[1], Hugo Sakai Idagawa[1], Ricardo Favaro[1]

[1]*Dept. of Techonoly, Senai Roberto Mange School and College of Technology*
Pastor Cicero Canuto de Lima Street, 71 São Bernardo - Vila Rialto, Campinas - SP, 13036-210
erick.battisotn@senaisp.edu.br, hugo.Sakai@sp.senai.br, ricardo.favaro@sp.senai.br

Abstract. Auxetic structures have aroused significant interest in the scientific community due to their unique properties of lateral expansion when subjected to tensile forces, and transverse deformation when subjected to negative Poisson's ratio. This article offers an analysis of these structures, where the theoretical foundations of the negative Poisson's ratio behind auxetic behavior are explored, including the mechanical properties that confer this characteristic. Using SolidWorks Simulation software, mechanical simulations of re-entrant auxetic structures were carried out, and we obtained displacement results equal to 0.690, 0.910 and 1.01 mm, under loads of 150, 200 and 220 kgf respectively. These conditions were reproduced experimentally, resulting in Poisson's ratio at -0,5, -0,625 and -0,777 under each of the previously mentioned loads. Auxetic structures have an example of application in Aeronautics, where they are used in aircraft components to improve impact resistance and energy absorption, increasing passenger safety. In the area of robotics, they also have applications to create flexible and resistant components, such as joints and coatings, which can withstand deformations without losing structural integrity.

Keywords: Auxetic structures, mechanical analysis, advanced materials, negative Poisson, metamaterial.

1 Introduction

The analysis of auxetic structures represents an innovative field in materials engineering, focusing on the study of auxetic materials and their application in additive manufacturing. The term “auxetic” is derived from the Greek word “auxetikos” and refers to “that which tends to increase,” as described by Evans and Alderson (2000). Auxetic materials exhibit a unique property of lateral expansion when stretched longitudinally, and longitudinal compression when compressed, distinguishing them from conventional materials. In this exploratory study, the potential of these materials in additive manufacturing was investigated by examining their structural properties and behavior during mechanical testing. This research aims not only to enhance the understanding of auxetic materials but also to explore their innovative applications in the development of complex and adaptable structures, fostering significant advancements in the manufacturing industry.

2 Instruction review

Auxetic materials exhibit a deformation behavior distinct from that of materials commonly applied in engineering. This behavior is related to their geometry, which confers a negative Poisson’s ratio, thereby

opening a new branch of applications. The following sections of this chapter delve deeper into this discussion.

2.1 Auxetic Materials

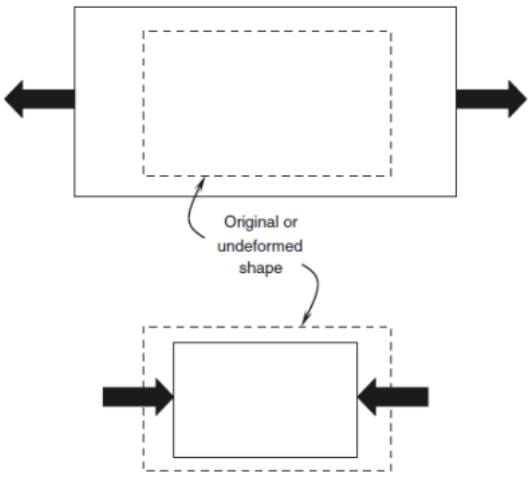
This property arises from their unique microscopic or macromolecular structure, which enables behavior opposite to that of conventional materials. According to Lvov et al. (2022), these materials have garnered increasing interest across various fields due to their unique characteristics, including biomedical engineering, protective materials, and damping applications, among others. The first study to observe this longitudinal and transverse deformation behavior was conducted by Young (1807). Subsequent research followed, with Cauchy (1827) deriving a coefficient based on molecular interaction theory. From this, it was established that the characterization of an isotropic material requires two independent elastic moduli (Young's modulus and shear modulus), which are related through the Poisson's ratio. Therefore, Poisson's ratio varies among different materials.

2.2 Poisson's Ratio

According to Lim (2015), Poisson's ratio is a measure of the relationship between transverse strain and axial strain of a material when subjected to uniaxial loading and is defined by Equation 1. In conventional materials, this ratio is positive, indicating that expansion in one direction is associated with contraction in

perpendicular directions. However, in auxetic materials, Poisson's ratio (ν) can be negative, as illustrated in Figure 1.

Figure 1 - Behavior of a material with a negative Poisson's ratio



$$\nu = -\frac{\varepsilon_{trans}}{\varepsilon_{long}}$$

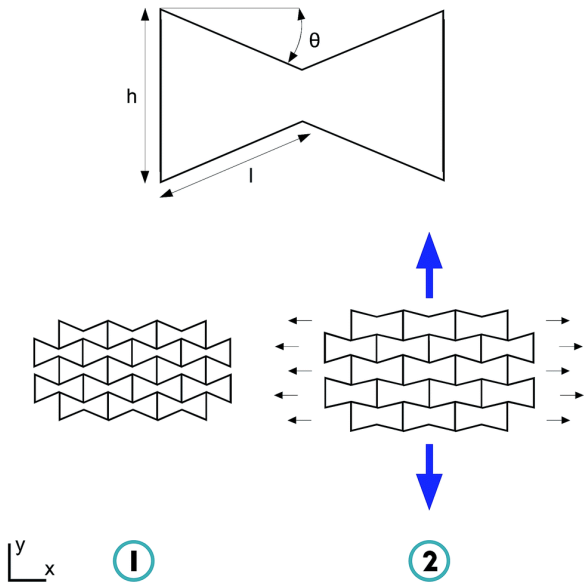
Source: Lim (2015)

2.3 Reentrant Structures

The ability of auxetic materials to expand laterally when stretched and contract when compressed is a phenomenon that has garnered increasing interest within the scientific community and materials industry. According to Evans and Alderson (2000), this unique property is attributed to their reentrant structure,

which is characterized by elements arranged to create repetitive patterns overlapping at multiple scales, as shown in Figure 2. This structural configuration provides auxetic materials with an exceptionally robust

Figure 2 - Re-entrant bow-tie structure with θ being the re-entrant angle, h/l being the cell rib length ratio and w being the thickness of the ribs. (1) In rest. (2) Tensile loading in y-direction.



Source: Delft University of Technology, Delft, Holanda. 17 de janeiro de 2017

2.4 Mechanical Testing

Mechanical testing consists of experimental procedures used to understand how materials behave under different loading conditions. In the study of auxetic materials, these tests are essential to determine how they expand, contract, and respond to various loading scenarios. For instance, tensile tests can be conducted to observe deformation behavior, compressive tests to evaluate contraction, and bending tests to assess responses to forces applied in different directions [4]. These experiments were performed using a KRATOS universal testing machine (Figure 3).

Figure 3 - Compression test on the universal testing machine



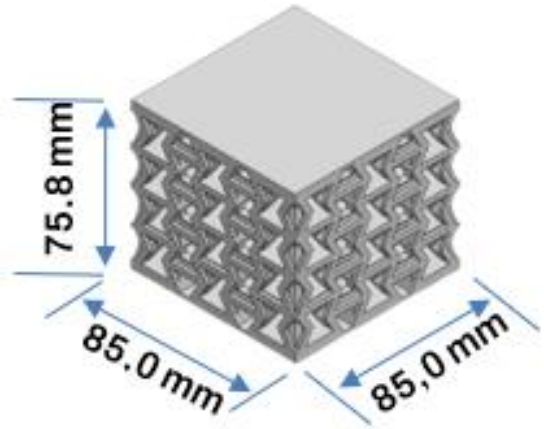
Source: Author's own

Among the various tests used to characterize materials, compression tests (Figure 3), in which a uniaxial load is applied to reduce the volume of the specimen, are especially relevant for auxetic materials, as they allow for the determination of the Poisson's ratio, as described by Pelleg (2013).

3 METHODOLOGY

Through research in the GrabCAD database (2024), a cube with a reentrant geometry was found, and the 3D model was evaluated using CAD software (Computer-Aided Design). The model dimensions are 85 mm in width, 85 mm in length, and 75.8 mm in height, as shown in Figure 5.

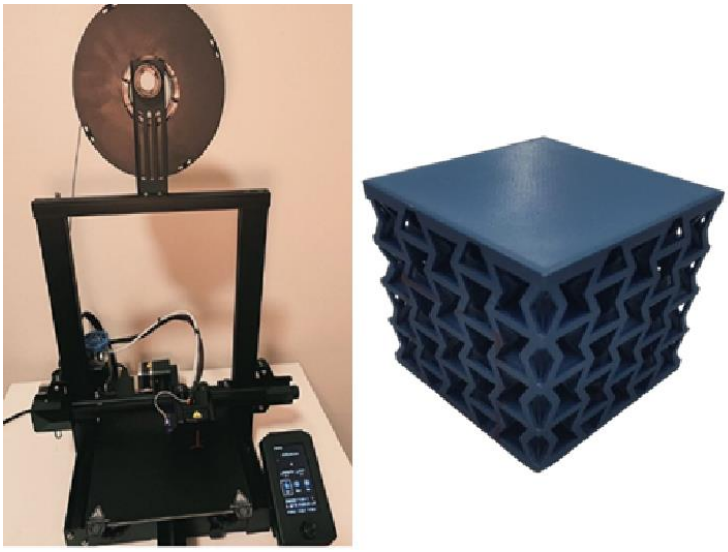
Figure 4 - Cube with Reentrant Structure



Source: Author's own

The 3D file was exported to an Ender 3 V2 Neo FDM (Fused Deposition Modeling) 3D printer (Figure 6) with an extrusion temperature of 235°C and a heated bed temperature of 80°C, and a printing speed of 50 mm/s. The polymer used was PETG (Polyethylene Terephthalate Glycol) (Figure 6), which has an elastic modulus of approximately 1 GPa, making the material both strong and flexible compared to other polymers commonly used in this type of printing, according to the manufacturer's specifications (3DLAB, 2024).

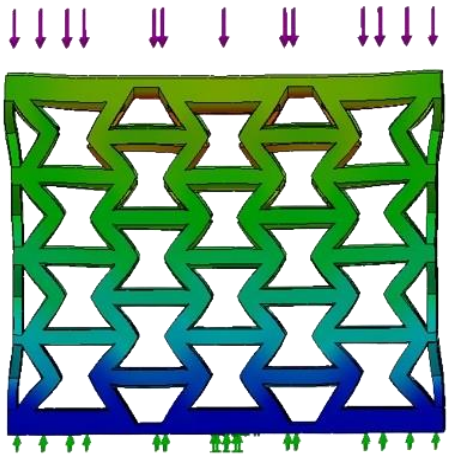
Figure 5 - 3D-printed cube with reentrant geometry



Source: Author's own

Using the CAD software SolidWorks with the finite element simulation tool, static compression analyses were performed on the specimen (Figure 8). Following the simulations, compression tests were conducted using the Kratos universal testing machine (Figure 3), which allows automation of test conditions and generation of reports with results in various units, calculations, and statistical data. The tests began with 5 compression cycles applying a load of 150 kgf at a displacement speed of 3 mm/min. To evaluate behavior under different conditions, the load was increased to 200 kgf and 220 kgf, maintaining the same number of cycles and displacement speed. Spatial measurements were taken using a Mitutoyo digital caliper with a 150 mm scale. The simulation results were compared to the experimental data and are presented in the following section.

Figure 6 - Static Analysis

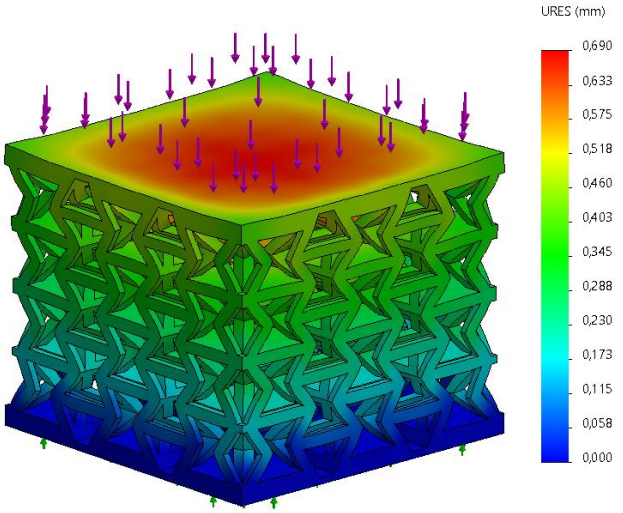


Source: Author's own

4 RESULTS AND DISCUSSION

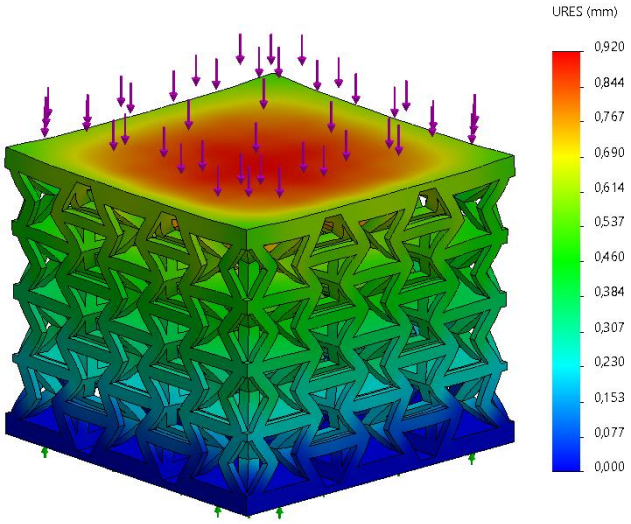
The results obtained from testing auxetic materials under different loading conditions reveal their remarkable adaptability. Through tests conducted using the CAD software SolidWorks Simulation with static loads of 150 kgf (Figure 10), 200 kgf (Figure 11), and 220 kgf (Figure 12), a significant longitudinal reduction from the initial measurement was observed. With the load still statically applied at the end of the cycles, spatial dimensions were measured, demonstrating that the specimen with reentrant structures possessed the necessary properties to behave as an auxetic material.

Figure 7 -Simulation with an applied load of 150 kgf, resulting in a displacement of 0.690 mm



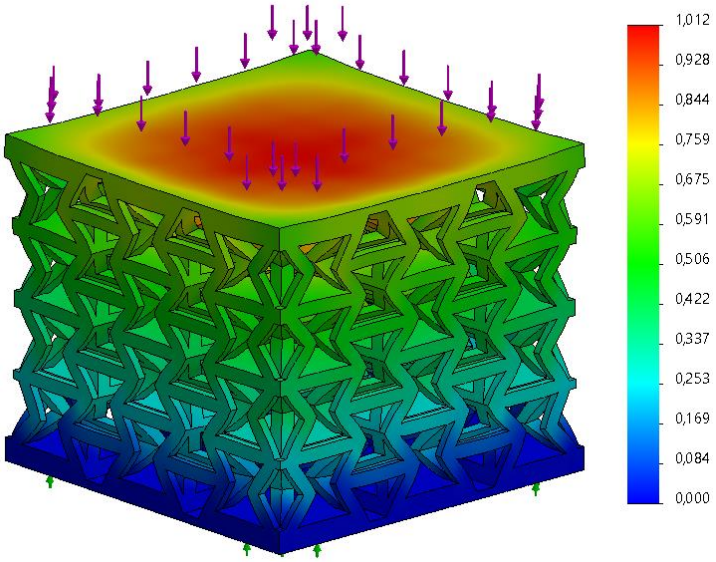
Source: Author's own

Figure 8 - Simulation with an applied load of 200 kgf, resulting in a displacement of 0.920 mm



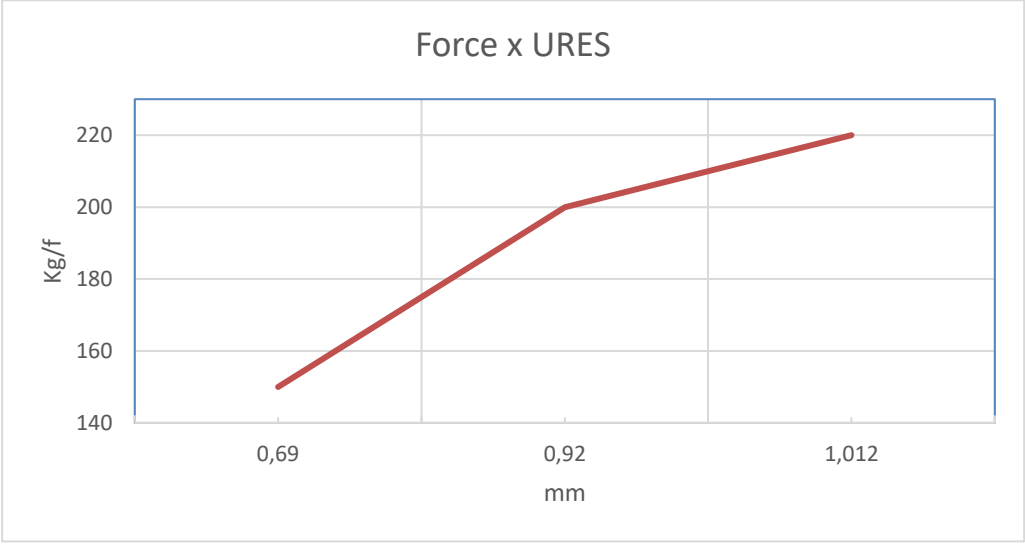
Source: Author's own

Figure 9 - Simulation with an applied load of 220 kgf, resulting in a displacement of 1.01 mm



Source: Author's own

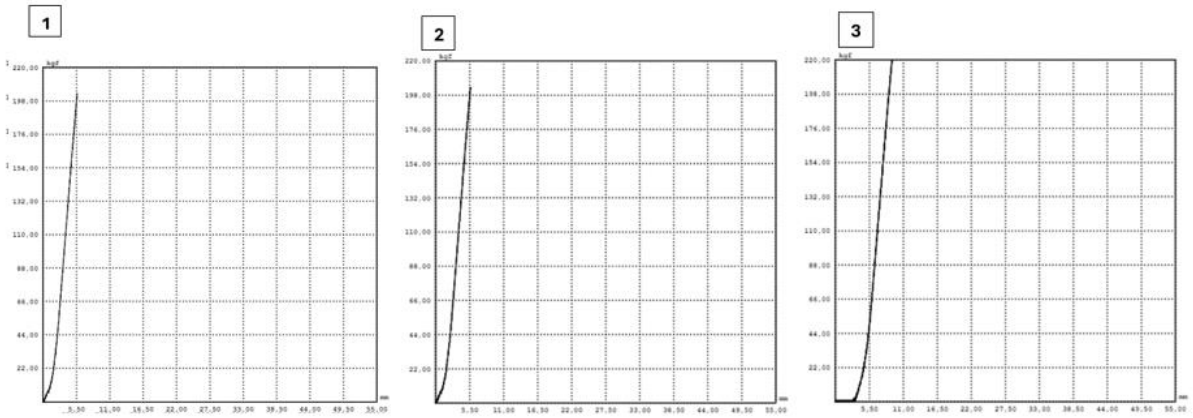
Table 1- Grafic Force x URES



Source: Author's own

Following the simulations, tests were carried out on the universal testing machine using the same loads applied in the SolidWorks Simulation. The results are shown in Figure 15. The material exhibited a linear behavior under compression testing, indicating that it remained within the elastic region. Furthermore, measurements taken under static loading conditions revealed a reduction in the longitudinal dimension, as shown in Table 1, which characterizes the material as auxetic.

Figure 10 - compression test



Source: Author's own

Tabela 1 - test specimen values after tests

Simulation	Force(Kg)	Ures(displacement mm)	ν (mechanical test)	Final measurements of the test specimen
Test 1	150	0,69	-0,5	84,6 x 84,6 x 75
Test 2	200	0,92	-0,625	84,3 x 84,3 x 75
Test 3	220	1,012	-0,777	84,3 x 84,3 x 74,9

Source: Author's own

The calculation for Poisson's ratio was the change in A (ΔA) divided by the change in B (ΔB). Since it's a cube, we can assume that the longitudinal reduction can be equal for both sides, so our equation only uses the change in one side (B).

The equation used to calculate negative Poisson's ratio was:

$$\text{Test 1} = -\nu = \frac{\Delta B}{\Delta A} = \frac{84{,}6-85}{75{,}8-75} = -0{,}5$$

$$\text{Test 2} = -\nu = \frac{\Delta B}{\Delta A} = \frac{84{,}5-85}{75{,}8-75} = -0{,}625$$

$$\text{Test 3} = -\nu = \frac{\Delta B}{\Delta A} = \frac{84{,}3-85}{74{,}9-75{,}8} = -0{,}777$$

It is possible to verify (experimentally) that, in the region of linear elasticity of the material, the

unit transverse compression is not proportional to the unit longitudinal compression.

Since both compressions are dimensionless, this constant will also be dimensionless.

5 CONCLUSION

The experiments conducted revealed difficulties in characterizing a material with the necessary auxetic characteristics. However, further research demonstrated satisfactory negative Poisson's ratio results, as indicated by graphs with linearity between force and displacement (URES). The test graphs also demonstrated linearity in the results, confirming that the material is auxetic and remains within the elastic range. This study highlights the need for expanded academic and collaborative research among engineers, technicians, and technologists. Interdisciplinary collaboration is essential to advance the understanding and application of auxetic structures, opening new perspectives for the development of innovative materials and devices.

References

EVANS, K. E.; ALDERSON, A. Auxetic materials: functional materials and structures from lateral thinking! Adv. Mater., v. 12, n. 9, p. 617–628, 2000.

BEER, F. P.; JOHNSTON, E. R.; DEWOLF, J. T. Mecânica dos Materiais. 3. ed. Portugal: McGraw-Hill, 2003

GRABCAD. Re-entrant auxetic structure. Disponível em: https://grabcad.com/library/re-entrant-auxetic-structure-1. Acesso em: 04 jun. 2024.

KHAN ACADEMY. What is Hooke's law? Disponível em: https://pt.khanacademy.org/science/physics/work-and-energy/hookes-law/a/what-is-hookes-law. Acesso em: 04 jun. 2024.

LAKES, R. Foam structures with a negative Poisson's ratio. Science, v. 235, p. 1038–1040, 1987.

LIM, T. Auxetic Materials and Structures. Springer, 2015. 587 p.

LVOV, V. A. et al. Auxetic metamaterials for biomedical devices: current situation, main challenges, and research trends. Materials, v. 15, n. 4, p. 1439, 2022.

MA, Y. et al. A nonlinear auxetic structural vibration damper with metal rubber particles. Smart Mater. Struct., v. 22, n. 8, p. 084012, 2013.

MAXWELL. Disponível em: https://www.maxwell.vrac.puc-rio.br/33148/33148.PDF. Acesso em: 04 jun. 2024.

PELLEG, J. Mechanical properties of materials. Dordrecht: Springer, 2013. 84 p. (Vol. 190).

ROYAL SOCIETY OF CHEMISTRY. Disponível em: https://pubs.rsc.org/en/content/articlehtml/2017/ra/c6ra27333e. Acesso em: 04 jun. 2024.

SAINT-VENANT. Résumé des leçons sur l'application de la mécanique à l'établissement des constructions et des machines. Premiere section, Paris, 1848.

VALENTE, M. N. Disponível em: https://www.ipb.pt/~mnvalente/2005-1sem/MA2/MA2-Introducao.pdf. Acesso em: 04 jun. 2024.

3DLAB. Disponível em: https://3dlab.com.br/. Acesso em: 02 jun. 2024.

ZADPOOR, A. A. Mechanical meta-materials. Mater. Horiz., v. 3, p. 371–381, 2016..