Experimental analysis of three tetra-anti-chiral auxetic honeycomb structures

Negrea Raluca¹, Predoiu Paul¹, Tabacu Stefan¹, Negrea Denis²

¹Faculty of Mechanics and Technology, University of Pitesti, Romania
²Regional Center of Research & Development for materials, processes and innovative products dedicated to the automotive industry (CRC&D-Auto), University of Pitesti, Romania
raluca.negrea@yahoo.ro

Abstract. Recent advances in manufacturing macro/micro/nano-structures led to the development of metamaterials, a new class of materials, which have exceptional properties, not easy to observe in nature, in terms of mechanical response, heat transport performance and energy absorption. In this study, a specific auxetic structure called anti-tetra-chiral, ATC (the adjective “chiral” means physical property to spin, “anti” is the effect, and the “tetra” represents their number of ligaments) is investigated and it was manufactured by laser cutting from 3 mm thick S320 mild steel plates with three different horizontal to vertical ligament ratios of 1:1, 1.5:1 and 1:1.5. The elastic properties of raw material, obtained by tensile testing regular S320 mild steel specimens, have been used in a numerical simulation algorithm using LS-DYNA in order to identify the loading capabilities of the structure. Then, an experimental setup for compression and tensile testing of A, B, and C types of ATC structures have been appropriately planned and performed, assisted by with Digital Image Correlation (DIC) analysis using GOM-Correlate in order to obtain the deformation field evolution and calculate the average Poisson’s coefficients for all three ACT structures. Future research work is targeted for the development and optimization of both ATC structure design and numerical simulation algorithm targeting shock absorbers applications.

1. Introduction
The concept of metamaterials (meta means ‘beyond’ in Greek) initially defined as new artificial materials with unusual electromagnetic properties that are not found in naturally occurring materials [1]. Metamaterials possess superior and unusual properties in terms of static modulus, density, energy absorption, acoustic and photonic performance, heat transport performance, intelligent materials, and negative Poisson’s ratio (NPR) [2].

The word “auxetic” is derived from the word αυχητικόξ (read: auxetikos), which means that it tends to grow. As it is known, most materials shrink in the transverse direction when drawn in the longitudinal direction or extend in the transverse direction when compressed in the longitudinal direction, which means they have a positive Poisson’s ratio (PR) [3]. The materials with negative Poisson’s ratio have a particular mechanical behavior because they extend in the transverse direction when they are loaded in the longitudinal direction. Due to this unusual behavior, the materials with negative Poisson’s ratio have several advantages such as high shear modulus, synclastic curvature,
high damping resistance, high fracture resistance, increased crack growth resistance, and high energy absorption capability.

Auxetic materials can be divided into four main groups as: auxetic honeycombs, - special subsets of foams, - auxetic microporous polymers, - long fiber composites [4] [5] [6]. Auxetic honeycomb structures can be investigated under four main types as 1. Re-entrant Structures, 2. Rotating Units, 3. Missing Rib, 4. Chiral Structures.

Chiral models are another kind of widely used cellular auxetic materials, and the word ‘chiral’ originally means a molecule that is non-superimposable on its mirror image. However, this term is often used to present a physical property of spinning.

The geometry of the unit cell is named by the Greek numbers: tri-, tetra-, penta- or hexa-chiral – the number depends on the number of ligaments (ribs) to central nodes which may be circles or other geometrical shapes. The chiral cellular solids have superiority over conventional hexagonal honeycombs, such as compressive and shear strengths [7] [8].

Their mechanical properties can be improved by using optimization methods depending on the purpose of their use. Recently, studies on their energy absorption capability and vibration transmission performance have increased [9]. And the development of additive manufacturing technologies supports the investigation of several auxiliary materials [10].

The tetra-anti-chiral (ATC) material structures, analyzed in this work, were manufactured by laser cutting of mild steel S320 [11]. Because the mechanical behavior of the structure depends on the base material properties, test samples have been cut and prepared for a tensile test to have an estimate of Young’s modulus. The auxetic structure was subjected to tensile and compressive loads, and the distribution of the relative deformation was determined using the method of digital image correlation, and a finite element model was developed.

Material information obtained on the previous experimental tests was implemented to the numerical model, and the generated results were compared with the results obtained by experimental testing.

The present work is focused on the investigation of a series of structures derived from the same base, with altered dimensions of the ligaments. The objective is to correlate the value of the computed Poisson’s ratio with the dimensions of the structure. This study presents the promising potential of tetra-anti-chiral materials for various versatile applications for the identification or for studying particular models and optimization [12] [13].

2. Experimental procedure

2.1. Material and specimen

Materials used in this research were 3 mm thick S320 mild steel plates, which have been laser cut into anti-tetra-chiral (ATC) structures with different horizontal to vertical ligament ratio as follows: A structure 1:1, B structure 1.5:1 and C structure 1:1.5 (Figure 1).

![Figure 1. Geometry and sizes of ATC structures (g-2,7mm, d-8mm, D-13,7mm, Lx:Ly – 20x20mm for A type structure, 30:20mm for B type structure, 20:30mm for C type structure)](image-url)
2.2. Testing machines

The conventional testing machine was used for quasi-static tests at the strain rate of 0.01 and 1 s\(^{-1}\), coupled with a hi-resolution digital camera for image acquisition (Figure 2).

The microcomputer-controlled electronic universal testing machine is capable of developing a displacement rate of 500 mm/min and data sampling at 1000 hertz.

![Figure 2. The universal testing machine, experimental setup a) specimen grip area b).](image)

2.3. Numerical modeling and digital image correlation analysis

To properly identify the maximum compressive and tensile loads that can be applied to the structure without plastic deformation of the ligaments, numerical simulations were performed. This step is necessary for the experimental program, as it is an efficient way to properly identify the loading capabilities of the structure while keeping the linear elastic behavior.

The numerical simulations presented in this paper were performed using LS-DYNA with the implicit solver option. The element type assigned to the model is a fully integrated solid element. The global element size is 1 mm. The top section of the structure was clamped by assigning a rigid material to a number of layers of elements.

The structure was loaded by a rigid body defined by several elements placed at the bottom of the structure, following a prescribed loading curve. This limit was set by a number of iterations considering the results (crushing force), global simulation output (energy balance, external work, energy ratio, and added mass) and computational effort (hardware resources, software requirements in terms of solver’s licensed CPUs and simulation time). The numerical model is presented in Figure 3.
The material model assigned to the deformable structures is *MAT_PIECEWISE_LINEAR_PLASTICITY. The Von Mises yield function (Φ) is implemented by:

\[
\Phi = \frac{1}{2} s_{ij}^2 - \frac{\sigma_y^2}{3} \leq 0
\]  

(1)

where \( s_{ij} \) is the deviatoric stress and \( \sigma_y \) is the current radius of yield surface defined:

\[
\sigma_y = \beta \cdot [\sigma_0 + f_h(\varepsilon_{eff}^p)]
\]  

(2)

\( f_h(\varepsilon_{eff}^p) \) is the hardening function defined by tabulated data considering the plastic strain \( \varepsilon_{eff}^p \). The material model has the capability of working with a true stress-strain curve (plastic), determined from experiments. It is also capable of accounting for the strain-rate effect in case of dynamic loading cases.

Digital Image Correlation (DIC) is an optical measurement technique that evaluates the deformation and displacement of a test specimen through a stochastic pattern [14] [15]. The sample is painted with white paint and then coded/pixelated by spraying with black paint. A digital camera is used to capture images during the test and save for enhancement procedures and analysis. DIC analysis of the three ATC structures was performed using GOM-Correlate software. During the analysis, the software can identify unique points from the stochastic pattern and, subsequently, to trace in the following recorded images. The difference of the points coordinates between the images can then be used to calculate the local strain, displacement, or deformation in all directions of the specimen.

3. Results and discussion
First, regular S320 mild steel specimens have been subjected to tensile testing in order to obtain the elastic properties of raw material. The experimental work followed the prescription of ASTM E8 (Standard Test Methods for Tension Testing of Metallic Materials). For the evaluation of the value of Young’s modulus, a 50mm electronic extensometer was fitted on the specimen. The obtained stress-strain data for the material are presented in Figure 4. The obtained data have been used in a numerical
simulation algorithm in order to identify the loading capabilities of the structure while keeping the linear elastic behavior.

![Engineering stress-strain curve](image1)

**Figure 4.** Stress-strain data for material S320.

- *a*) engineering stress-strain curve;
- *b*) true stress-strain curve.

The loading curve was defined by a number of loading steps from the minimum load up to a user-defined maximum load. For each step, the load was kept constant for a while.

Figure 5 presents the stress and plastic strain distribution during loading displayed by the structure. Figure 5. *a*) presents the structure at the stage when the maximum stress was recorded, while Figure 5. *b*) presents the plastic strain distribution at the end of the loading program.

![Results of the numerical simulation](image2)

**Figure 5.** Results of the numerical simulation

- *a*) stress state;
- *b*) plastic strain state.

The numerical simulation allows for the identification of the limit load before any permanent deformations of the structure are recorded. Figure 6 presents the loading steps and the evolution of the plastic strain during loading.
Figure 6. Plastic strain vs. loading stage a) compressive load; b) tensile load.

Once the loading capabilities of the structure for keeping the linear elastic behavior have been set, the experimental elastic range (an important issue in case of structures undergoing cyclic loadings).

Figure 7. Force displacement data.

a) Structures under compressive load; b) Structures under tensile loads.

Figure 8-10 shows the deformation field evolution of the A, B, and C types ATC structures, freeze at the frames of
Figure 9. GOM Analysis. Structure B: $30 \times 20$ mm

Figure 10. GOM Analysis. Structure C: $20 \times 30$ mm

Figure 11 shows the average Poisson’s coefficient values obtained by DIC for all the preset points pairs on the spec

Figure 11. Poisson’s coefficient and Stages analysis $a)$ for type A $20\times20$mm, $b)$ B $30\times20$mm, and $c)$ C $30\times20$mm ATC structures.
Based on the information obtained from DIC analysis (Figure 11), the Poisson’s coefficient was calculated with mean values of -0.90, -0.48 and -1.38 for A, B, and C type ATC structures, with the ratio of the lengths of the ligaments of 1:1, 1:1.5 and 1.5:1.

4. Conclusion
In this paper, is presented the investigation of three anti-tetra-chiral material structures with different horizontal to vertical ligament ratio (A structure 1:1, B structure 1.5:1 and C structure 1:1.5), manufactured by laser cutting from 3 mm thick S320 mild steel plates. First, regular S320 mild steel specimens have been subjected to tensile testing in order to obtain the elastic properties of raw material. The obtained data have been used in a numerical simulation algorithm in order to identify the loading capabilities of the structure while keeping the linear elastic behavior. The obtained results have been used to plan and perform a proper experimental setup for compression and tensile testing of A, B, and C types of ATC structures. Digital Image Correlation (DIC) analysis of the three ATC structures was performed using GOM-Correlate software in order to obtain the deformation field evolution and calculate Poisson’s coefficient. Both data sets obtained confirmed the auxetic behavior of the analyzed ATC structures and a correlation between dimensions and Poisson’s ratio.

The values are in agreement with the geometrical features of the tested structure. This shows that the design process can be started from simple assumptions.

Future research work is targeted for the development and optimization of both ATC structure design and numerical simulation algorithm.

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