STRUCTURAL SIMULATION OF SUSTAINABLE AUXETIC CELL BASED ON RUBBER WASTES

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Abstract. *The growing demand for tyres has been every year exacerbating environmental problems due to indiscriminate disposal in nature, making a waste potentially harmful to public health. The reuse of waste tyres as a dispersive phase in polymeric composites has been investigated, exhibiting satisfactory mechanical properties, especially high toughness. The auxetic materials are multi re-entrant honeycomb structures assembled to achieve a negative Poisson´s ratio. The properties such as low density, high toughness and mechanical strength make them useful as body armour, packaging solutions, knee and elbow pads and robust shock absorbing materials. The addition of recycled rubber as dispersive phase of polymeric composites within an auxetic structure could therefore provide a relatively low cost and highly mechanical efficient solution in energy absorption applications. The elastic properties of the sustainable polymeric composites reinforced with rubber particles were obtained by compressive testing. This work investigates the mechanical behaviour of this sustainable composite designed as an auxetic cell using the finite element method. The sustainable auxetic structure exhibited a negative Poisson's ratio, revealing that the investigated material has a significant potential for this application.*

Keywords*: auxetic, cellular material, composite*

1. INTRODUCTION (Times New Roman, bold, size 10)

Cellular solids are widely used in a variety of engineering applications. The honeycomb structures are very common mainly in aircraft and aerospace industry, where a high strength and a low density are required for the development of high performance composite materials. A metamaterial is an artificially produced material, which is endowed with properties that do not exist in nature. Among these materials, the reentrant structures are highlighted, exhibiting a negative Poisson's ratio.

The Poisson's ratio (υ) is the ratio between the transverse and longitudinal specific strain and, for the most engineering materials this coefficient is always positive, around 0.3.

The mechanical behaviour of a material with negative Poisson's ratio means a reduction of its cross section under compression and a perpendicular expansion under tensile loadings. As observed in Figure 1 the negative effect is due to the geometric characteristic of the reentrant unit cell [1].

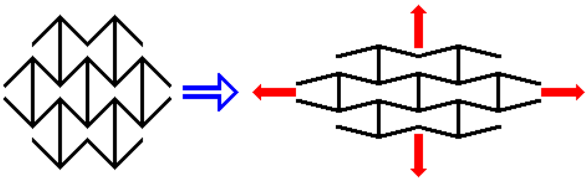

Figure 1 - Operation of the microstructure Auxetic

This metamaterial, known as "Auxetic" has been widely investigated for much applications, i.e. in the bulletproof vests, whose principle is based on the material's ability to compress as the projectile moves forward, and thus preventing its penetration [2, 3].

Although a negative Poisson´s ratio has not been ignored in the literature, only in 1987, Lakes made the first discovery about the negative effect of Poisson´s ratio designing a polyurethane foam (PU) with reentrant structures, which was named by anti-rubber, auxetic or dilatational [4]. The studies related to auxetic structures were mainly focused on the estimation of effective properties as a function of geometric dimensions [5], density variations [6], electromagnetic, acoustic and mechanical properties [7,8], and the ability to absorb vibrations [9] and so on.

According to the theory of cellular materials [1], the mechanical properties of a cellular solid can be described by geometric parameters of the unit cell and the mechanical properties of the manufactured material. The geometric arrangement of an unit cell, exhibited in Figure 2, can be represented by the relations α and β and the internal angle θ of the cell. The regular honeycomb cells (Figure 2a) have an extension of α equal to 1 and an angle θ of the inner cell equal to 30 °, while auxetic cells are characterized by negative internal angles (Figure 2b).

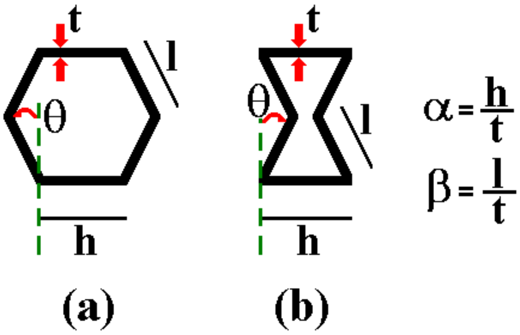

Figure 2 - Geometrical characteristics (a) regular cell and (b) cell Auxetic.

Yang et al. [4] reported that the elastic properties could be modified by varying the relative values of force for different deformation mechanisms. Depending on the geometry of the cell, the properties can be considered isotropic (for regular hexagons) or extremely anisotropic. The analysis is done considering the linear material properties. In addition, a range of materials have been modelled and investigated as reentrant structures [3-9].

The growing demand for tyres has been every year exacerbating environmental problems due to indiscriminate disposal in nature, making a waste potentially harmful to public health [10, 11]. Statistics show that in Brazil 300,000 tons of scrap rubber are generated per year, of which only 10% are recycled. In the U.S., the levels of scrap rubber per year are ten times higher, and only 5% are recycled [12]. The incorporation of scrap tire rubber into polymeric composites has obtained moderate strength and high toughness, allowing the reuse of this waste as a dispersive phase of particulate composites. This work investigates the mechanical behaviour of different auxetic structures made of a rubber composite material developed by Panzera et al [13. Representative volume element (RVE) models, using finite element analysis (FEA), have been employed to predict the Poisson's ratio of Auxetic cells.

2. MATERIAL AND METHOD

The data obtained numerically through the finite element method were compared using a statistical methodology based on Design of Experiment (DOE) [14-15]. Reentrant cells of different geometries were analyzed based on the cell characteristics as shown in Figure (3).

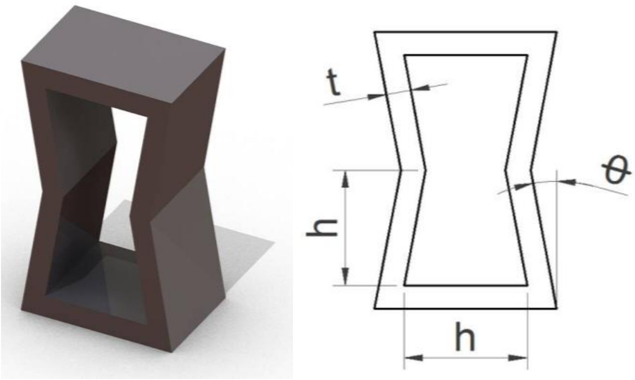

Figure 3 - Reentrant unit cell characteristics

Table 1 exhibits the experimental conditions investigated in this work by varying the factors: height (10 and 20mm), thickness (2 and 4mm) and internal cell angle (-10 ° to -20 °). The width dimension of 10 mm was constant for all cells.

Table 1 - Experimental conditions

Setup	Internal width and height (h)	Thickness (t)	Internal angle (θ)
C1	10	2	-10º

C2	10	2	-20º
C3	10	4	-10º
C4	10	4	-20º
C5	20	2	-10º
C6	20	2	-20º
C7	20	4	-10º
C8	20	4	-20º

According to Panzera et al. [12] the polymeric composite made with 25% of rubber particles size 50/80 US-Tyler exhibited satisfactory mechanical properties, especially high toughness. The composite material made of rubber particles can be considered isotropic, exhibiting elastic modulus (E) of 2.12 GPa and Poisson ratio of 0.28 The mesh was generated with tetrahedral elements of size 0.7 mm, (see Figure 4a). The boundary conditions were the bezel at the bottom of the cell and the applied force at the top of the cell, Figure 4b. The numerical testing was carried out by the finite element method using Abaqus SimuliaTM software (version 6.8.2).

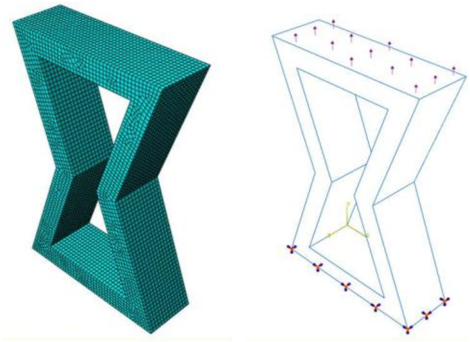

Figure 4. (a) Mesh and (b) boundary conditions of the cell.

The strain field of a cell was determined through the use of tensile forces ranging from 100N to 10 kN. High strain levels were observed not only at the centre (see Figure 5a), but also at the top of the cell due to the transverse deformation, (see Figure 5b).

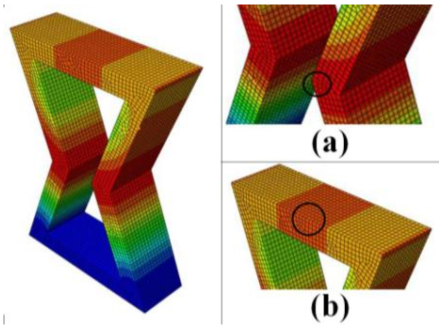

Figure 5. Strain field of auxetic cell and strain concentration areas.

3. RESULTS

Figure 6 shows the graph of transverse (x-axis) versus longitudinal (y-axis) strains of a unit cell for all experimental conditions. It is possible to observe C3 and C8 exhibiting the extreme limits.

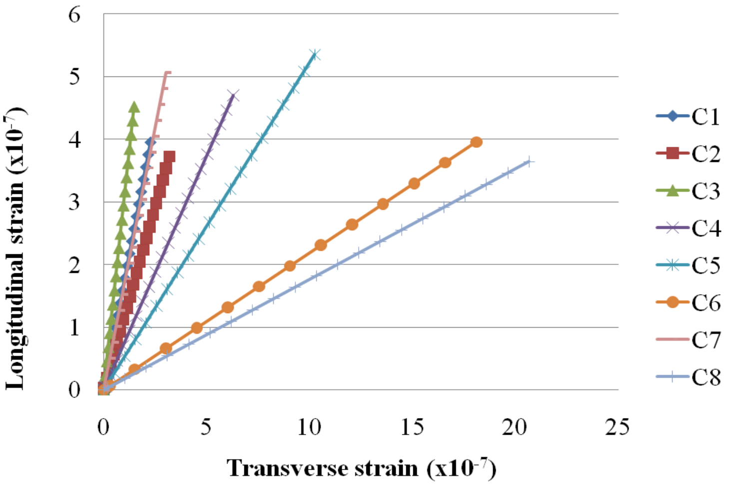

Figure 6. Transverse and longitudinal strains for the setup conditions

Based on numerical data the negative Poisson's ratios were determined for each cell (C1 to C8) using the Equation (1), see Table 2. The composites C6 and C8 exhibited inferior Poisson’s ratio values.

$$\upsilon = \frac{-\varepsilon_{lateral}}{\varepsilon_{Longitudinal}}$$

Table 2 - Values of Poisson's ratio.

Cell	Poisson ratio		Cell	Poisson ratio
C1	-0,58		C5	-1,92
C2	-0,86		C6	-4,58
C3	-0,33		C7	-0,59
C4	-1,34		C8	-5,67

In order to verify the effect of each factor on the Poisson´s ratio of reentrant structures, a design of experiment was conducted (DOE). The P-values (Table 3) indicate which of the effects in the system are statistically significant. If the P-value is less than or equal to 0.05 the effect is considered significant. An α-level of 0.05 is the level of significance which implies that there is 95% of probability of the effect being significant. The results will be presented via ‘main effect’ and ‘interaction’ plots. These graphic plots cannot be considered typical ‘scatter’ plots, but serve to illustrate the statistical analysis and provide the variation on the significant effects. The main effect of a factor must be interpreted individually only if there is no evidence that one factor does not interact with other factors. When one or more interaction effects of superior order are significant, the factors that interact must be considered jointly [14, 15]. A third order interaction (WH*T*A), underlined in Table 3, showed a significant effect on the Poisson´s ratio, exhibiting a P-value of 0.000. The interaction effect plot for the Poisson´s ratio can be seen in Figure 7.

Table 3 - Analysis of variance (ANOVA)

	Factors	P-value
Main factors	Internal width and height cell (WH)	0.000
	Thickness (T)	0.000
	Angle (A)	0.004
Interaction of factors	WH * T	0.000
	WH * A	0.000
	T * A	0.000
	WH * T * A	<u>0.000</u>
	R2-adj	99.68%

The increasing of the cell width provided the reduction of Poisson ratios (see Figure 7a and 7b). The width and height level of 20mm provided lower values of negative Poisson's ratio. Figure 7a shows a small variation of Poisson´s ratio from the low and high levels of thickness. However, it is possible to observe in Figure 7b the effect of the factors angle-width and height on the response, verifying a superior variation when the cell is manufactured with 20mm of width and height. A percent increasing of 342% it is observed when the width and height of 20mm change from low (-20) and high (-10) levels of angle factor.

Figure 7c exhibits the interaction effect of thickness angle factors on the Poisson´s ratio. It can be verified a diverse behaviour between these factors, the thickness of 4mm provides lower values of Poisson´s ration when the angle cell is set as -20°. On the other hand, this behaviour is altered for the angle cell level of -10°. A significant percent variation of Poisson´s ratio (693%) can be observed between the angle levels. The lowest Poisson's ratio is achieved when the auxetic cell is manufactured with: 4mm of thickness, -20° of angle and 20mm of internal width and height.

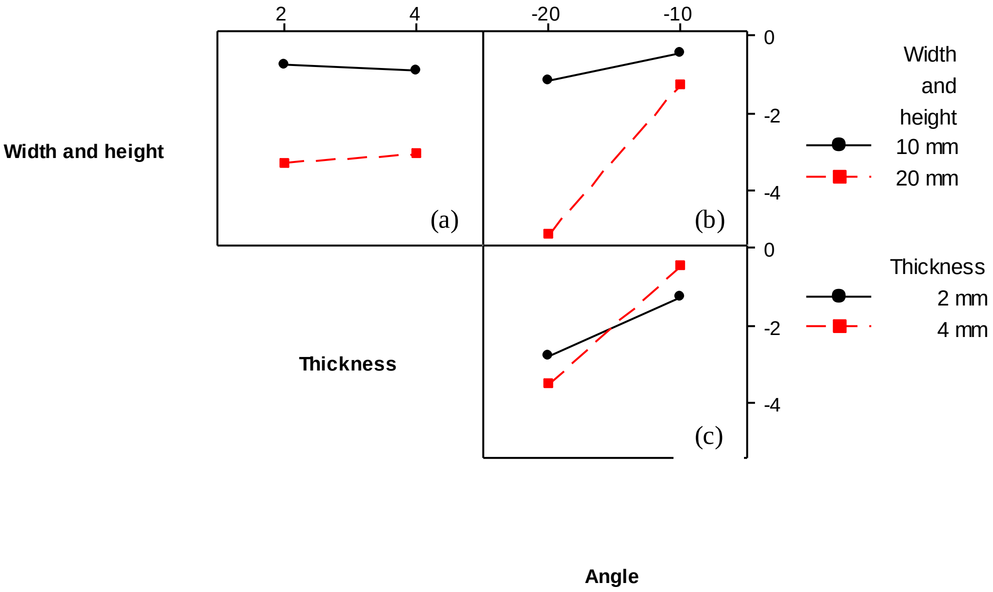

Figure 7. Interaction effect plot for the Poisson´s ratio.

4. CONCLUSIONS

A numerical simulation was carried out in order to verify the use of particulate polymeric composites constituted of rubber wastes as an auxetic structure. In addition, a design of experiment (DOE) was performed identifying the cell geometry factor effects on the Poisson´s ratio response. The main conclusions and effects will be now described:

(i) The finite element method was able to estimate the transverse and longitudinal strains of re-entrant cells under tensile forces.

(ii) The interaction effect of the geometric factors affected significantly the Poisson's ratio of the unit re-entrant cell.

(iii) Not only the internal width and height factor but also the angle of the cell exhibited a relevant effect on the Poisson´s ratio. Higher width and height provided lower values of Poisson´s ratio. Lower cell angles provided lower values of Poisson´s ratio.

(iv) The thickness factor exhibited an interesting effect on the response, exhibiting opposite behaviours when the angle of the cell is changed.

(v) The sustainable composite made of rubber particles exhibited satisfactory performances as auxetic structures, becoming an alternative material for this proposal.

(vi) The DOE was able to identify the factor effects on the response, showing the percentage variations of each factor on the Poisson´s ratio of a unique cell.

5. ACKNOWLEGMENT

The financial support of FAPEMIG is gratefully acknowledged.

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