

Article

Introducing Auxetic Behavior to Syntactic Foams

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Abstract: This paper proposes an innovative multi-material approach for introducing auxetic behaviour to syntactic foams (SFs). By carefully designing the size, shape, and orientation of the SFs, auxetic deformation behaviour was induced. Re-entrant hexagon-shaped SF elements were fabricated using expanded perlite (EP) particles and a plaster of Paris slurry first. Then, an auxetic pattern of these SF elements was arranged within a stainless-steel casting box. The empty spaces between the SF elements were filled with molten aluminium alloy (A356) using the counter-gravity infiltration casting technique. The cast auxetic composite had a bulk density of 1.52 g/cm³. The cast composite was then compressed under quasi-static loading to characterise its deformation behaviour and to determine the mechanical properties, especially the Poisson's ratio. The cast composite deformation was auxetic with a Poisson's ratio of −1.04. Finite Element (FE) simulations were conducted to understand the deformation mechanism better and provide means for further optimisation of the geometry.

Keywords: auxetic cellular structures; syntactic foams; experimental testing; mechanical properties; Poisson's ratio

1. Introduction

Syntactic foams (SFs) and metallic foams [1–4] are lightweight materials with a high strength-to-weight ratio, offering a broad range of potential applications in the construction and automotive industries. Ceramic syntactic foams have been extensively researched for their ability to withstand harsh environmental conditions, including high temperatures, corrosive media, and radiation [5,6]. Different ceramic matrices, such as cement [7], are manufactured using microballoons. The study investigated a cement-based syntactic foam core for composite sandwich structures featuring microballoons dispersed in a rubber-latex-toughened cement paste matrix. With varying cement content, the foam demonstrated higher impact energy dissipation and comparable strength to a polymer-based foam, making it a potential alternative for impact-tolerant composite sandwich structures. In [8], a lightweight cementitious SF was produced using hollow glass microspheres. Varying microsphere densities (0.15–0.60 g/cm³) and volume fractions (20–50%) resulted in compressive strengths (32–88 MPa) and elastic moduli (10–20 GPa) within a low-density range (1.15–1.80 g/cm³). Micro-CT scans revealed density-dependent micro-fracture mechanisms in compressive loading. In [9], a syntactic foam was manufactured through a one-part mix of geopolymer and ecospheres, exhibiting impressive mechanical and thermal performance compared to existing lightweight concretes and composites. The geopolymer–cenosphere mixture, activated by water and cured at ambient temperature, formed a robust interfacial layer according to synchrotron-based FTIR analysis. The resulting foam displayed a 56-day compressive strength of 17.5 MPa at a density of 978 kg/m³ and a thermal conductivity of 0.28 W/m·K, making it suitable for lightweight structural applications in energy-efficient buildings.

Auxetic materials exhibit negative Poisson ratios [10,11]; this behaviour is highly desirable for applications where resilience and energy absorption are important [12]. Different



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types of auxetic materials have been investigated recently [13–17]. Re-entrant auxetic structures were fabricated using the Abrasive Water Jet (AWJ) cutting technology from a 3 mm thick sheet made of the aluminium alloy 7075-T651 [18]. These structures exhibit unique properties, such as a negative Poisson's ratio. The research explored the impact of unit cell orientation on crack paths and fatigue life through experimental and computational methods. Low Cycle Fatigue (LCF) tests were conducted, and computational models using ANSYS 2022 software were employed to simulate their mechanical behaviour. The results indicated that while unit cell orientation had a minor effect on fatigue life, it significantly influenced the direction of fatigue failure paths in the analysed auxetic structures. Xue et al. [19] fabricated the auxetic lattice structures based on commercially pure aluminium using 3D printing and investment casting technologies. Their research involved fabricating an aluminium-based auxetic lattice structure reinforced with polymer fillers using pressure infiltration technology. The compressive mechanical properties of the resulting auxetic composites were investigated through experimental tests and finite element analyses. The findings revealed that the composites exhibit higher elastic modulus, compressive strength and energy absorption capacity than the original aluminium-based auxetic lattice structures. This improvement is attributed to increased interaction between the struts and polymer fillers resulting from the unique deformation mode of auxetic lattice structures. The study also discussed the deformation mechanism of auxetic structures and their corresponding composites, suggesting a significant enhancement in auxetic lattice structures when the negative Poisson's ratio effect is restrained. Quasi-static and impact behaviour of foam-filled graded auxetic panels was investigated experimentally and numerically in [20]. In this research, the auxetic structures were manufactured using a cost-effective method through corrugating and gluing the aluminium alloy sheets by incorporating polyurethane (PU) foams to create foam-filled samples. Compression tests were conducted at varying loading velocities (quasi-static and dynamic) using a universal testing machine and a drop tower. The mechanical properties of aluminium and PU foam were determined accordingly. Results showed that increasing sheet thickness enhanced specific energy absorption (SEA) capabilities in quasi-static and dynamic testing. Foam-filled auxetic panels exhibited superior energy absorption compared to empty panels. The crush force efficiency (CFE), a critical parameter for crash absorbers, decreased for uniform auxetic panels in dynamic loading but remained comparable for graded auxetic panels, including foam-filled samples. Finite element (FE) models accurately represented mechanical and deformation behaviour, showcasing auxetic response at large strains. In [21], a novel method for fabricating auxetic panels, employing a polyurethane foam core and thin stainless steel face sheets with a 2D auxetic pattern, was studied. The metallic face sheets are easily prepared using basic UV lithography and assembled with the core through adhesive bonding, resulting in a robust and easily handled sandwich panel suitable for structural applications. Tensile and bending tests were conducted to investigate the mechanical behaviour, and a Taguchi method-based parametric analysis, supported by Finite Element Analysis (FEA), was employed to assess the impact of geometric parameters and material properties on auxetic behaviour. The sandwich panel, featuring stainless steel face sheets with a “re-entrant sinusoidal” pattern and a homogeneous polyurethane foam core, exhibits successful auxetic behaviour under both tensile and bending loads.

The current research employs an innovative approach by integrating SF elements with re-entrant hexagon-shaped structures composed of EP particles and a plaster of Paris matrix, along with a metallic auxetic pattern (A356 aluminium alloy). This approach creates a novel composite material using a counter-gravity infiltration casting technique for the first time. To the best of the authors' knowledge, no similar composite structure has been developed by any other manufacturing techniques yet. Most of the research studies in the field of metallic auxetic structures have focused on manufacturing the samples using other techniques, as described earlier in this literature review. The new design in the current research is potentially attractive for various structural applications. The proposed approach also has several advantages over traditional methods for introducing auxetic

behaviour. First, it is a versatile approach that can be used with various syntactic foam matrices. Second, it is a scalable approach that can create syntactic foams at different scales. Third, it is a relatively simple and cheap approach that does not require specialised and expensive manufacturing techniques.

2. Material and Methods

2.1. Design

The metallic matrix of re-entrant hexagon unit cells (Figure 1) was chosen to realise auxetic deformation behaviour in the composite foam material. This configuration, previously established to exhibit auxetic properties [22–24], comprises individual re-entrant hexagon (“hourglass”) shapes as an inverse space. These voids were filled with a lightweight syntactic foam material, serving two essential functions: reinforcing the auxetic composite and acting as a space holder during casting.

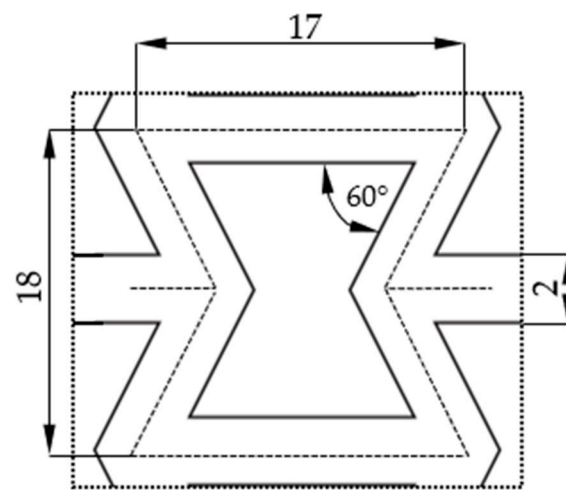


Figure 1. The re-entrant hexagon unit cell of the metallic phase auxetic geometry (all dimensions in mm).

The arrangement of the unit cells is shown in Figure 2a, where the positioning of the 7×3 unit cells in the aluminium matrix and the syntactic foam inserts are shown.

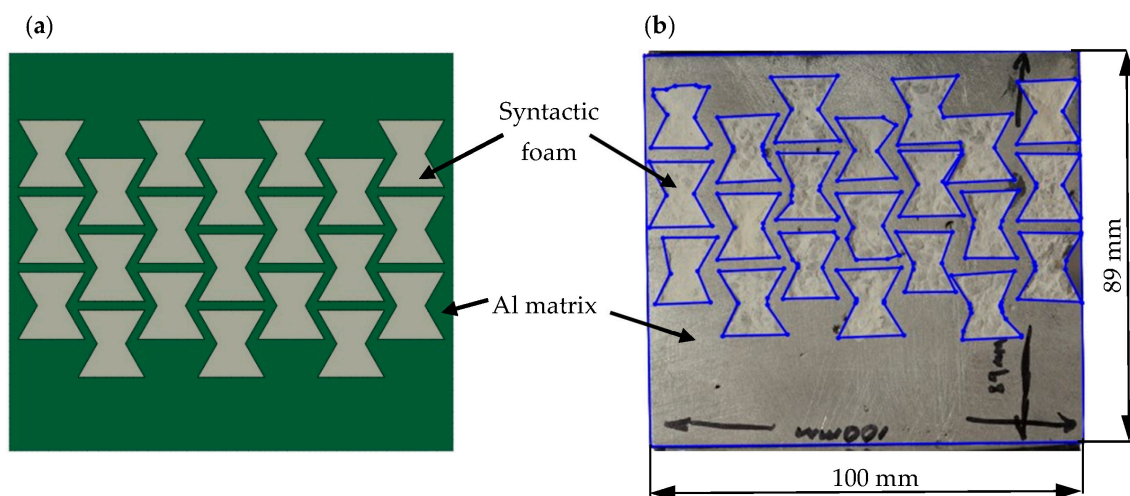


Figure 2. The geometry of the ideal (a) and fabricated (b) sample with marked (blue lines) actual sample geometry.

2.2. Fabrication

Re-entrant hexagon unit cell elements were crafted from a lightweight syntactic foam composed of expanded perlite (EP) particles and plaster of Paris. The EP particles, sourced from Ausperl Pty Ltd., Padstow, Australia, were filtered through 2.8 mm and 2.0 mm meshes, with only those retained by the 2.0 mm mesh being utilised. These porous particles exhibit low particle density, ranging from 0.16 to 0.18 g/cm³, making them lightweight [25]. According to the supplier data sheet, the chemical composition of the EP particles is as follows: 75 wt.% SiO₂, 14 wt.% Al₂O₃, 3 wt.%, Na₂O, 4 wt.% K₂O, 1.3 wt.% CaO, 1 wt.% Fe₂O₃, 0.3 wt.% MgO, 0.2 wt.%, TiO₂ with trace amount of heavy metal [26]. The EP particles were then carefully filled into 3D-printed moulds designed to replicate the desired hourglass geometry.

Following this, a plaster of Paris slurry with a volume ratio 2:1 (plaster to water) was added to the moulds in four equally proportioned batches. Between batches, the moulds underwent tapping to eliminate air bubbles and ensure a consistent slurry distribution among the EP particles. After an initial curing period of 4 h, the syntactic foam components were removed from the mould. Subsequently, the foam elements underwent a drying process at 500 °C for 5 h to eliminate any residual moisture. Subsequently, the foam elements were coated with Zirconium powder to improve wettability during casting.

To synthesise the auxetic syntactic foam, the re-entrant unit cells were arranged within a stainless-steel casting box with internal dimensions of 300 mm × 30 mm × 100 mm. The distribution of re-entrant cells within the box involved periodic placement with 2 mm gaps between adjacent units, resulting in 7 re-entrant cells per row, as illustrated in Figure 2. Excess aluminium can be seen at the upper and particularly lower sample volumes. Due to the solid aluminium matrix's significantly higher stiffness and strength, these regions underwent minimal deformation compared to the auxetic structure and were not removed prior to testing.

An A356 aluminium alloy, with alloying elements of 6.5–7.5 wt.% Si, 0.25–0.45 wt.% Mg [27] was chosen as the casting alloy. Approximately 300 g of this material was carefully introduced into the casting crucible. The casting mould was placed into the same crucible atop the solid aluminium alloy, housing the strategically positioned hourglass shapes. The assembly was subjected to heating at 720 °C. Upon achieving the liquefaction of the A356 alloy, a compressive force was applied to the casting mould, pushing it into the crucible and displacing the molten A356. Subsequently, the alloy was forced into the channels between the hourglass shapes before cooling under atmospheric conditions. As the counter-gravity infiltration casting occurs within a closed system comprising a mould and crucible, direct measurement of the molten aluminium alloy temperature during manufacturing stages is not feasible [28]. The casting box containing the SF elements was positioned upside down within the casting crucible, which held 300 g of the A356 aluminium alloy. This assembly was then placed in an electrical furnace and heated gradually from room temperature to 720 °C (the temperature set for the casting furnace). After one hour, upon reaching the liquefaction of the A356 alloy, a compressive force was applied to the casting mould, pushing it into the crucible and displacing the molten A356. Subsequently, the alloy was directed into the channels between the SF elements before cooling under atmospheric conditions. The compression force for infiltration was applied using a manual system comprising a rotational spindle without a pressure force measuring device.

The fabricated geometry is shown in Figure 2, where some fabrication defects are visible. These defects arise from the limited movement of the re-entrant cells during melt infiltration. The re-entrant foam elements were secured at room temperature using a pyrolysed adhesive during pre-heating. Fixation at high temperatures occurs through compressive forces between the casting box and foam elements. It is recommended to elevate the initial height of foam elements to amplify frictional forces with the casting box to enhance fixation.

3. Experimental Results

Compressive testing of one fabricated sample was conducted on a 50 kN Shimadzu uni-axial testing machine. Only one sample was used in this research to test the method of design and fabrication. However, more samples need to be tested in future work to provide statistically significant results. The sample was positioned between two stainless steel compression platens and compressed at a quasi-static loading velocity of 0.2 mm/s, as shown in Figure 3. Before the test, the sample's top surface was machine-cut to guarantee a good contact surface and parallel alignment between the sample and the steel heads. Additionally, the sample's out of-plane surfaces were cleaned and may have had some excess aluminium removed using silicon carbide sandpaper.



Figure 3. The experimental setup.

The deformation behaviour of the sample is shown in Figure 4, where the yellow dashed and red solid lines for evaluating the Poisson's ratio and the formation of the cracks (red and green circle) are marked. With green circles, the cracks formatted at the edge are marked, which appear at the very beginning of the loading regime and are a consequence of fabrication defects. The red circle shows the crack formatting in the middle of the sample, where the material of the auxetic matrix fails at approx. 0.01 strain.

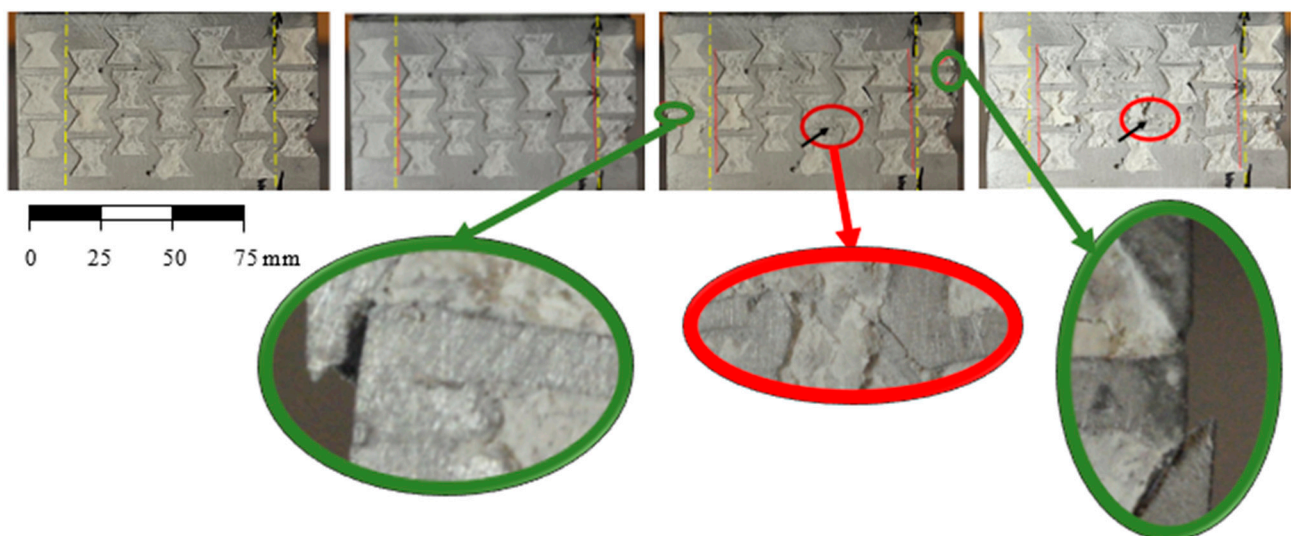


Figure 4. Deformation behaviour of the sample with marked and detailed location of the cracks (strain increment: 1%).

Figure 5 shows the compressive stress–strain data of the auxetic syntactic foam, where the engineering stress–strain values are calculated using the initial sample's geometry.

Following settling effects at low strains, an approximately linear elastic stress increase can be observed. This segment terminates in a slight stress oscillation that coincides with the fracture of aluminium struts at the edges of the sample, which is marked with green circles in Figure 4. Additionally, some separation between the matrix and SF appears, which is highlighted by a red circle in Figure 4 and can be observed in the middle of the sample. At higher strains, the engineering stress stabilises around 5 MPa and gradually declines for strains $\varepsilon > 0.045$.

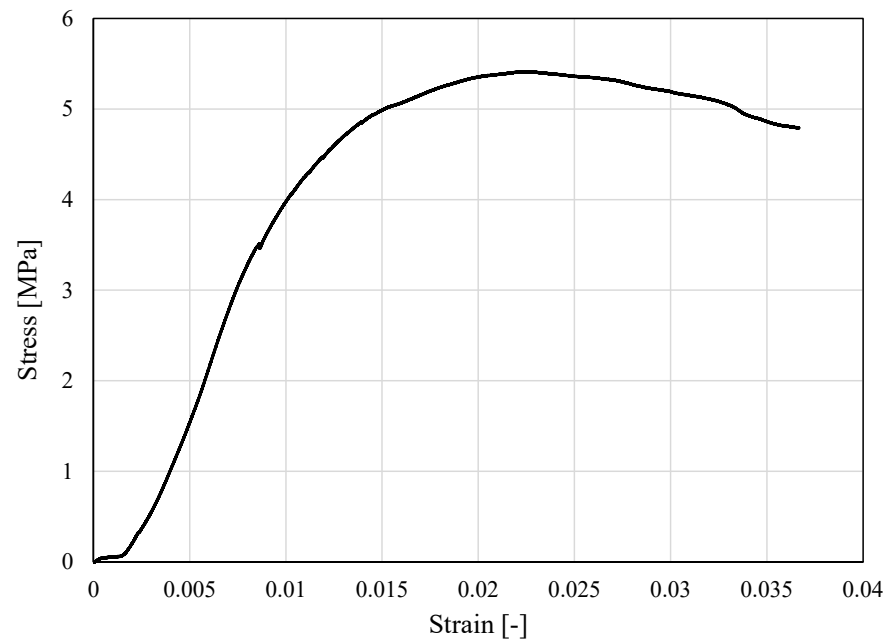


Figure 5. Experimentally determined engineering stress–strain relationship.

High-resolution light photographs were captured with a frequency of 0.1 Hz during compressive testing. Image analysis was used to determine Poisson’s ratio using the geometrical distances dx and dy indicated in Figure 6. Figure 7 shows the variation in Poisson’s ratio until the maximum tested longitudinal strain ($\varepsilon = 0.036$). The results demonstrate a very high initial Poisson’s ratio of $\nu = -1.004$, which reduces only slightly during the plastic deformation until maximum tested strain, proving a distinct auxetic behaviour of the structure.

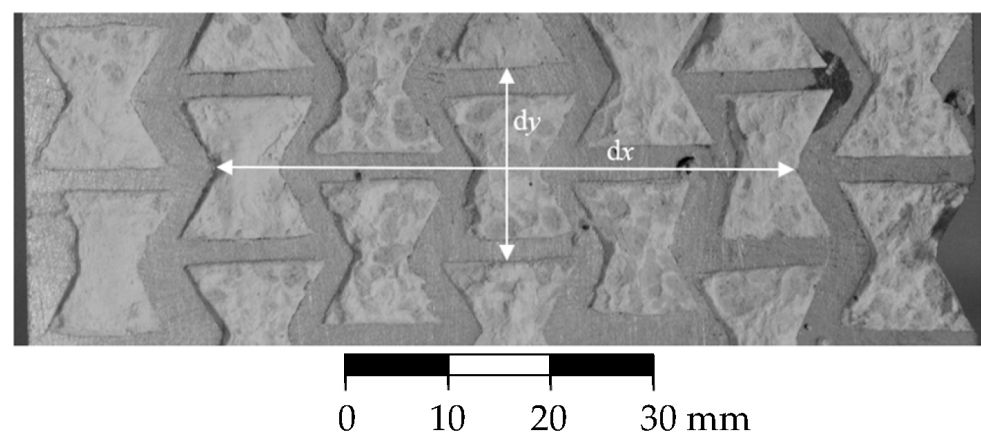


Figure 6. Optical measurement of Poisson’s ratio.

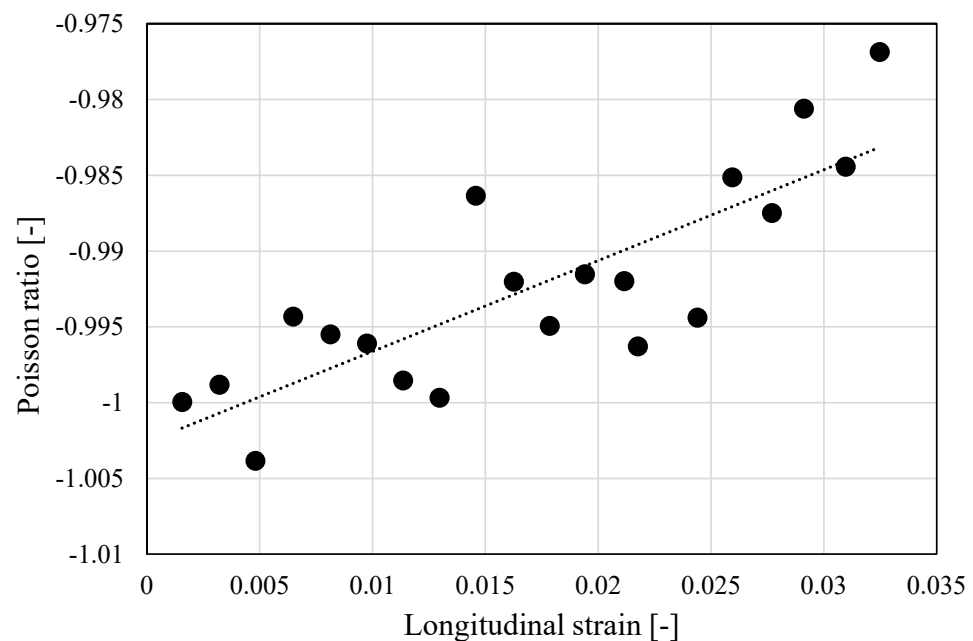


Figure 7. Variation in the Poisson's ratio with longitudinal strain.

4. Results of Computational Simulations and Discussion

4.1. Computational Model

The simple two-dimensional computational model was used in this research in order to evaluate the different geometry of the samples quickly and reliably. The basic geometry of the computational model was built in Solidworks 2024 software as a surface by scaling and then tracing the photo of the actual specimen (Figure 2). The 2D surface was then transferred to another program for FEM analysis called PrePoMax [29]. The model was divided into two parts, the outer matrix with an auxetic pattern made of aluminium and the inserts made of syntactic foam. The material parameters are shown in Table 1.

Table 1. Material data.

	ρ [kg/m ³]	E [MPa]	ν [22–24]
Aluminium	2700	3000	0.33
Syntactic foam	1020	60	0.3

The finite element mesh for the auxetic matrix consists of 1636 parabolic triangular elements (type S6), with an average global size of 3 mm, and the mesh for inserts consists of 1310 elements the same size as the matrix. The appropriate size of elements was determined with the convergence study with four different finite element sizes: 10, 8, 6, 4, and 2.5 mm.

The tied surface interaction was prescribed between the matrix and inserts so that the parts could not overlap. The matrix was defined as the master region, and inserts were defined as the slave region.

The upper edge of the model was prescribed with a displacement of 2 mm in the negative direction of the y -axis, as shown in Figure 8. The bottom edge was fixed (all displacement and rotations are disabled). Additionally, extra support was added on the front surface with z -axis displacement constrained, preventing the entire structure from deflecting in an out-of-plane direction. The implicit static calculation step with the default solver was used for calculation.

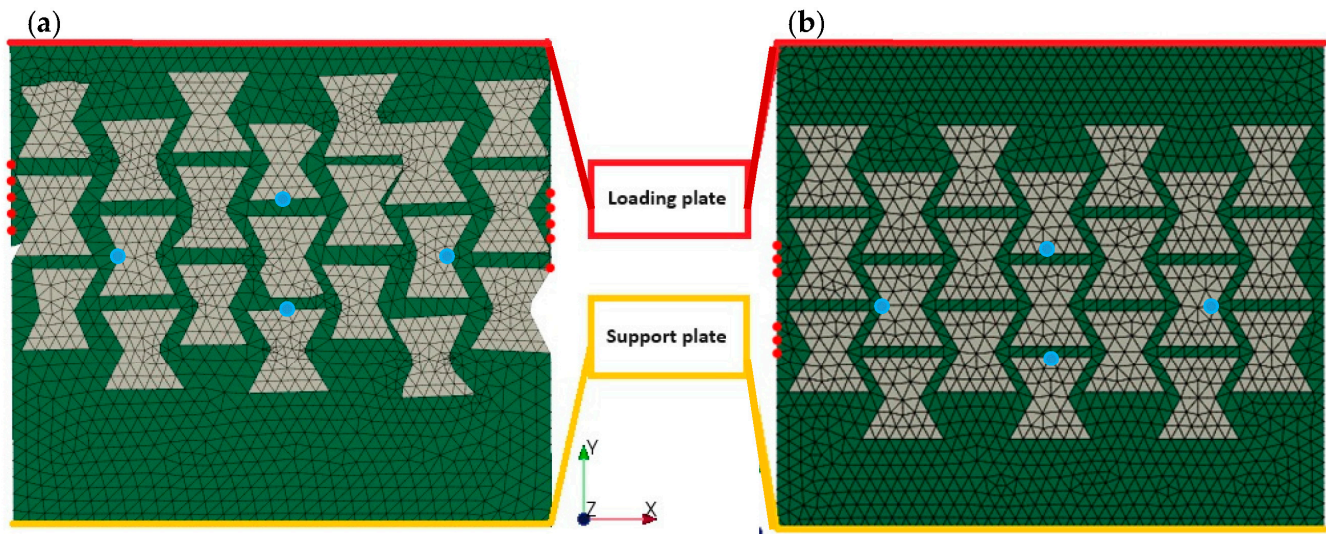


Figure 8. The FE models of actual (a) and idealised (b) sample with marked nodes (red and blue points) for evaluation of transversal strain.

Two different methods were used to determine the transversal deformation, which was used to calculate the engineering Poisson's ratio. The nodes on the edges and in the middle of the sample (to avoid boundary effect) were selected and are marked with blue dots on Figure 8. The blue dots provide information on the deformation behaviour of the inner representative unit of the sample. On the other hand, the red dots provide information on the movement of the edge of the sample.

In addition to the actual geometry, an idealised model without any fabrication errors was created (all inserts are the same shape, and the distance between them is constant, as shown in Figure 1). The same parameters and boundary conditions were used to simulate the experimental subject's ideal shape and actual shape.

4.2. Computational Results and Validation

The elastic parameters for both materials in the computational model were determined from quasi-static tests conducted separately for each material, followed by a comparison of experimental and computational responses. The material parameters for aluminium and syntactic foam are provided in Table 1, where ρ is density, E is Young's modulus, and ν is Poisson's ratio.

The deformation behaviour comparison of the experimental sample and actual and idealised FE models is presented in Figure 9. The actual FE model provides detailed insights into the non-symmetrical deformation behaviour of the metamaterial due to the fabrication defects. The idealised model (Figure 9c) deforms symmetrically and exhibits visible auxetic behaviour. The syntactic foam inserts offer support for the matrix, which decreases the stress concentration at the edges of the matrix structure.

As shown in Figure 10, the reaction forces acting on the support plate of the simulation and the experiment are similar. However, when plastic deformation occurs in the experimental testing, the force declines more rapidly than in the purely elastic simulation. To improve the agreement at higher strains, the computational model must include plastic material behaviour, which will be carried out in our future work. As already expected from the deformation behaviour (Figure 9), the simulation of the ideal geometry results in a stiffer response than the actual geometry, although the ideal model based on geometry shown in Figure 2a has a 7% lower amount of aluminium matrix phase in the area of the re-entrant unit cells.

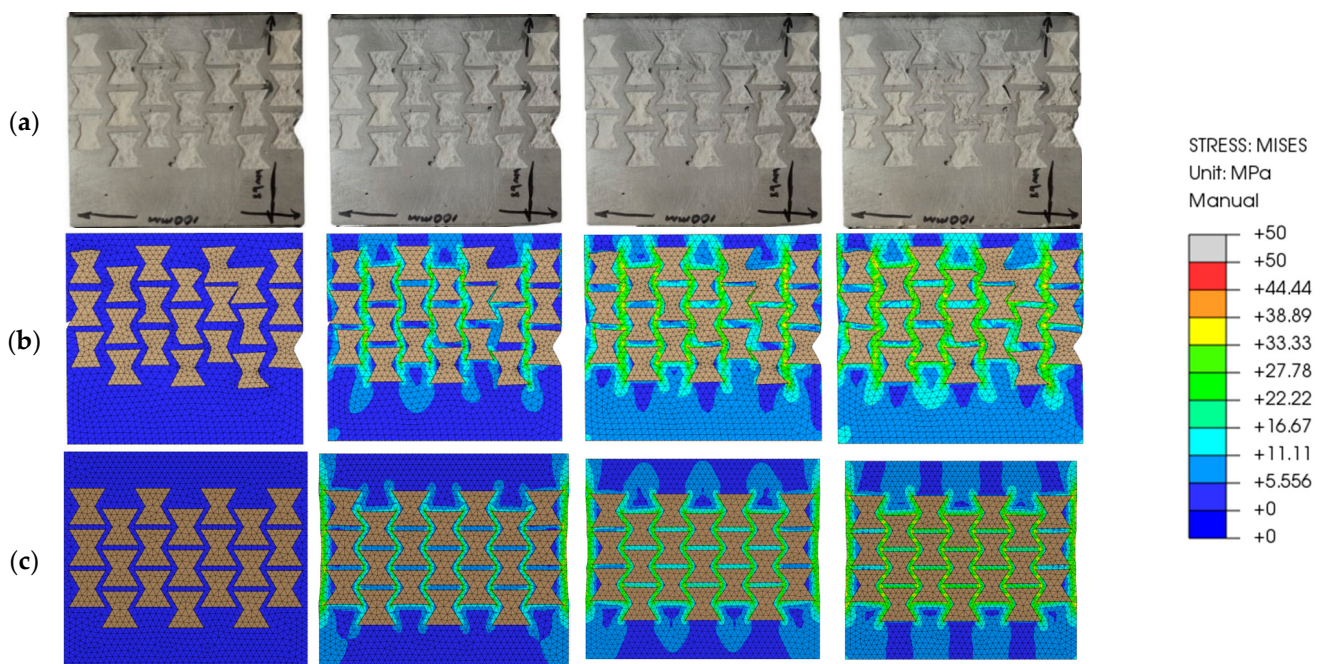


Figure 9. The comparison of experimental (a), actual FE model's (b) and idealised FE model's (c) deformation behaviour (strain increment: 0.75%).

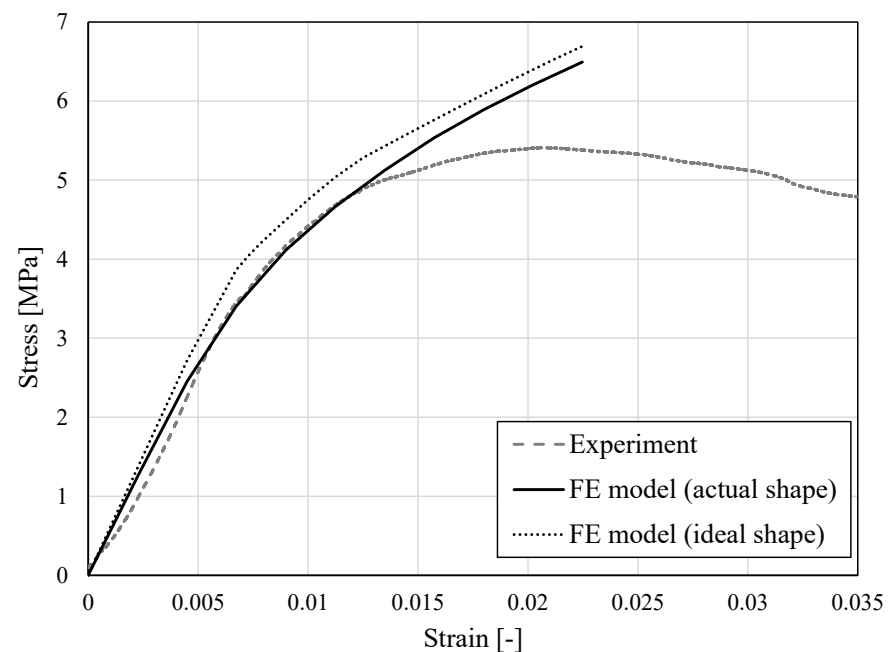


Figure 10. The experimental and computational results comparison.

The validated computational models enable the study of different geometries. The structure with a wider auxetic phase, named here also as “Ideal v2”, was developed and virtually tested to study the influence of the stiffness ratio between the matrix and SF phase on the deformation response. The Ideal v2 structure is compared to ideal structures at the same strain level in Figure 11. It can be seen that the stresses are up to 100 MPa in the structure with wider auxetic struts since the matrix is stiffer and at the same global compressive deformation which results in higher stresses in the structure. This showed that with the adaption or optimisation of the matrix geometry, the load-bearing capabilities of the structure can be easily tailored to the specific need of the application.

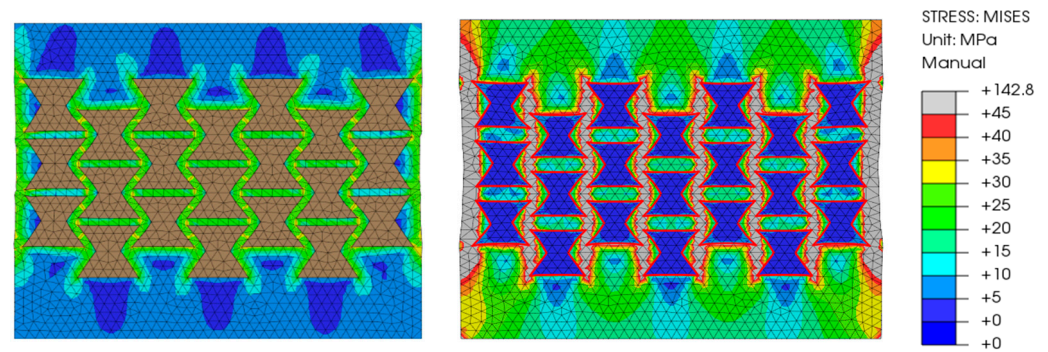


Figure 11. The comparison between the Von Mises stress state of Ideal and Ideal v2 shapes at 2.25% strain.

Besides evaluating the mechanical response, the displacements of the structure were also measured transversely and longitudinally to the loading direction during the test using two different approaches. This allowed us to determine the Poisson's ratio of all three models (the actual shape, the ideal shape and the ideal shape with a wider auxetic phase) with respect to the longitudinal deformation of the model. The points where the displacements were measured are marked in Figure 8 with red and blue dots. In the idealised model, only displacements on one side were measured, as the response on the other side is symmetric. In the case of the actual shape, the displacements on the left and right sides were evaluated because responses are not symmetric.

The Poisson's ratio variation with longitudinal strain is shown in Figure 12. When observing the internal part of the sample, the comparison with the experimental values shows relatively good agreement. The only major difference is that the Poisson's ratio values are more or less constant at a value of -1 in the experiment up to 2% strain, while the FE model values constantly decrease. This could result from local plastic deformation in the experiments, which is not captured in the FE model. All the shapes deform auxetically in the observed range of strains, while only the Ideal shape v2 sample provides the linear response because its struts do not undergo local buckling.

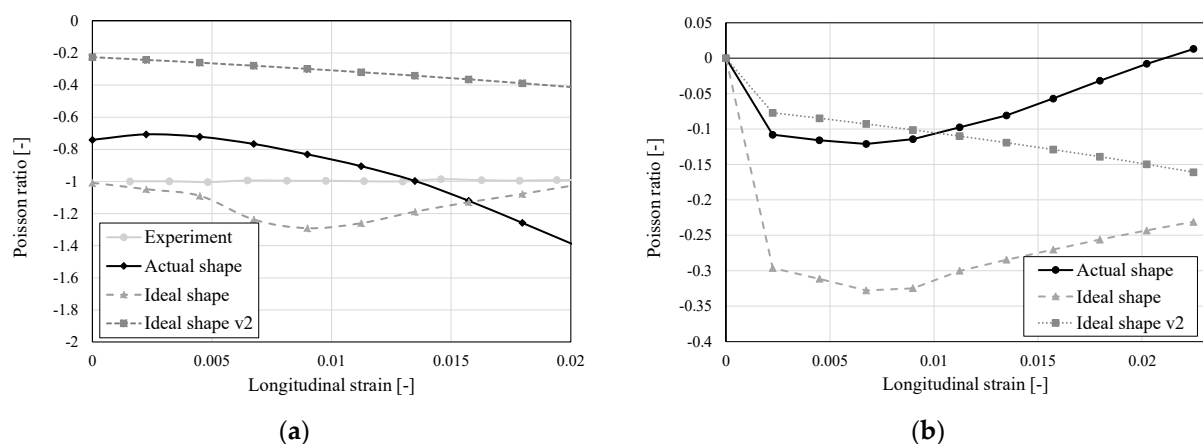


Figure 12. The Poisson's ratio dependency on the longitudinal strain: middle of the sample (a) and tracking edge (b).

When observing the deformation at the edge of the sample (Figure 12b), it can be observed that the model with the actual shape initially behaves like an auxetic material. At higher longitudinal deformations, the Poisson's ratio reaches a positive value. On the other hand, the ideal shape samples provide a more significant auxetic response up to all ranges of analysed strains (the Poisson's ratio is decreased from -0.12 to -0.32). The increase in the thickness of matrix struts in the case of the Ideal shape v2 model results in slightly

less negative values of Poisson's ratio (increase from -0.32 to -0.16), which is caused by the changed stiffness ratio between the matrix and foam filler. For all models with the perfect specimen shape, it can be seen by both methods that the models behave like auxetic material throughout the simulation.

5. Conclusions

This paper presents a novel multi-material method for creating auxetic syntactic foams (SFs). The novel multi-material composite, consisting of an aluminium matrix and syntactic foam as a filler, was successfully designed and fabricated using the counter-gravity infiltration casting technique. The fabricated sample was then tested under the quasi-static compression loading, and the results confirmed the negative Poisson ratio. Furthermore, the computational models were developed, which provide detailed insight into the samples' deformation behaviour and offer the possibility to explore further options for optimising the geometry and fabrication procedure. The results of the computational model of the ideal shape indicate that a more pronounced auxetic effect can be achieved compared to the fabricated geometry, so it is suggested to optimise the fabrication procedure.

Combining experimental and computational methods strengthens the findings and paves the way for further optimisation of the material's design, where with a slight modification to the matrix geometry, the auxetic behaviour can be further enhanced. The findings also hold promise for applications requiring materials with a negative Poisson ratio, such as energy absorption and vibration damping. Future studies will consider different sizes of re-entrant unit cells (i.e., different amounts of unit cells within the casting box), different unit cells geometries (i.e., use of chiral or missing rib geometries) and different gap liquid flows in the channel.

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