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Analysis of additively manufactured (3D printed) dual-material auxetic structures under compression

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Abstract

Auxetic cellular structures offer improvements in some mechanical properties due to their negative Poisson's ratio response when loaded. This study investigates and compares the effect of using multiple materials within three well researched cellular geometries, two auxetic: re-entrant and anti-tetrachiral, and one non-auxetic: hexagonal honeycomb. For each geometry, three different material configurations were used, a single material PLA structure and two dual-material structures: Polylactic Acid (PLA) - Nylon and PLA - Thermoplastic Polyurethane (TPU). A numerical model was developed to simulate these complex multi-material cellular geometries under a quasi-static compression load using Abaqus Explicit solver. To validate this numerical model, samples were additively manufactured and experimentally tested. They were found to show good correlation for the PLA and PLA-TPU. This study found that for situations where single loading cycles were required, for example, for crashworthy structures, the single material structures offered the highest performance where they absorbed the largest amount of energy. If multiple loading cycles are required, the multi-material structures offer the best solution due to the compression occurring through elastic buckling in comparison to plastic buckling in the single material. It was also found that through introducing materials with varying stiffnesses into specific regions within the structure, the Poisson's ratio through the compression could be modified for the re-entrant and honeycomb geometries.

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1 Introduction

In our fast-evolving society, there is a continuous requirement to develop ever lighter structures for different loading situations. A common method of achieving this is the use of sandwich panels where two sheet materials are bonded to a core material which is commonly made of a cellular structure. The geometry of these structures is an area which has been intensely researched [1]. One of the most utilised geometries as cores are honeycomb cells, shown in Figure 1, which offer high specific stiffness when orientated in the out-of-plane direction [2]. Loading in the in-plane direction is however of interest due to its energy-absorbing capabilities caused by the deformation of the cells which converts kinetic energy into other energy forms, primarily heat via plasticity, viscosity, viscoelasticity or friction. Energy absorption structures have various applications including crash-worthy structures such as cars, bullet-proof vests and transport packaging.

Figure 1. Honeycomb cell structure loading mechanisms

An area which provides promise for this in-plane loading is auxetic materials. By definition, auxetic structures present a counter-intuitive geometrical response under loading as they exhibit a negative Poisson's ratio response. This means that when a tensile load applied in the longitudinal direction, the auxetic structure also stretches in the transverse direction, illustrated in Figure 2. Under an applied compression load, an auxetic will densify and contract orthogonal to the direction of loading. This mechanism causes auxetic materials to display superior material properties namely impact resistance, fracture toughness and vibration transmission.

Figure 2. Re-entrant auxetic response (a) No-loading (b) Under uni-axial tension [3]

Studies have been undertaken to develop different auxetic architectures in order to improve the auxetic effect which in turn can improve properties such as the energy absorption [4]–[8]. Some of the most promising geometries are shown in Figure 3 [9]. Each geometry offers differing characteristics, for example, the anti-tetrachiral has been shown to provide the largest auxetic effect with the lowest Poisson's ratio, however, the double arrowhead shows the highest stiffness [10]. A number of studies have also looked at creating methods to optimise these structures, so to improve the properties of these structures relative to their mass due to their desired characteristics for high-performance lightweight applications. Optimisation methods have included topology optimisation [11], homogenisation [12] and genetic algorithms [13].

Figure 3. Auxetic Geometries [9]

Due to the enhanced properties offered by these auxetic structures, they have potential for a range of industries. This includes areas where blast mitigation is required [14] such as the undercarriage of military vehicles, blast-proof vests and buildings, or areas where impact resistance is critical which includes crash-worthy structures or sporting applications like exercise mats and helmets [15]. A new design strategy [16] was developed for the internal structure of turbine blades that makes use of auxetic architected materials tailored to reduce stresses and temperatures throughout the blade. They have also seen adoption in the medical industry for their geometrical response where these structures have been utilised for a new stent design [17].

Additive manufacturing is a fast-developing field due to the advantages it provides in design and development, and increasingly for manufacturing [18-21]. Recently, Han and Lee [18] reviewed recent advances in multi-material additive manufacturing. This process offers several different manufacturing techniques which aren't possible through traditional manufacturing. This includes the integration of multiple materials within a single structure without the need for post-processing to join the materials [22]. This has a range of potential applications such as printing full products in one process, for example, dentures could be printed with one material for the gums and a harder material for the teeth [23]. Another use of this multi-material printing is the creation of compliant mechanisms [24], where materials of varying stiffnesses are used to allow rotations in specific regions of a structure. This blending of materials could have huge implications for manufacturing as it reduces the need for extra joining processes such as fasteners or adhesives, saving time and money for manufacturers.

The use of multiple materials in auxetic structures is an area receiving attention [25-31]. Wang et al. [25] designed a collection of dual-material auxetic materials and they investigated the influence of design parameters on auxeticity and equivalent Young's modulus. Mirzaali et al. [26,27] showed that a multi-material design could lead a wide range of elastic properties. Su et al. [28] investigated a unique dual-material auxetic structure with reinforcement arches which increase the structure stiffness significantly. Ng et al. [29] studied the dual-material re-entrant triangle with a negative thermal expansion capability. Zhang et al. [30] presented a new bi-material microstructural design method and topology optimization to achieve chiral auxetic properties. Saxena et al. [31] analysed the effect of using multi materials on the auxetic behavior, strain sensitivity and cellular stiffness.

In these previous studies, it was found that through introducing materials with varying stiffness within specific regions in the auxetic architecture, the negative Poisson's ratio motion could be improved. These initial studies have been limited and currently have only identified their potential to improve the auxetic response and not the critical mechanical properties of the structures such as the specific energy absorption.

In this study, we analyse different auxetic structures and introduce materials of varying stiffness within their architecture and compare their properties, with a focus on the effect on the Poisson's ratio and their energy absorption properties. This study looks at two well researched auxetic architectures: re-entrant and anti-tetrachiral and introduce multiple materials within their structure and compare the results. A non-auxetic hexagonal honeycomb cellular structure is also examined to compare this with the auxetic structures. Although data sheets exist for the materials utilised in this study, the materials are characterised due to the altered properties resulting from the anisotropic nature of the additive manufacture process. Due to the complexity of the architecture of these multi-material cellular structures, a method for analysing these geometries through a Finite Element Analysis (FEA) is developed for a quasi-static compression load. To validate this numerical model, the structures are additively manufactured and then tested experimentally.

2 Methodology

2.1 Specimen Geometry

In this study three different geometries were analysed, two of which were auxetic geometries; re-entrant and anti-tetrachiral, and one non-auxetic; hexagonal honeycomb. These geometries were selected due to their differing characteristics shown from Elipe and Lantada's comparative study [10]. The dimensions of the geometries were selected to reduce the brittle material failure that occurred in the structures up until the densification stage of compression. This allowed the geometry to be the determining feature on the deformation instead of the failure of the material which is not within the scope of this study. Figure 4 shows the unit cell geometries utilised in this study. The darker regions of the structure show where the material of a lower stiffness will be placed. Full dimensions of these structures can be found in Figure 5.

Figure 4. Unit cell geometries and material selection used in this study

Figure 5. Geometry parameters

2.2 Material Characterisation

Three different materials were selected for this study to be utilised in the cellular architectures: Polylactic Acid (PLA), Nylon and Thermoplastic Polyurethane (TPU). These materials were selected due to their differing stiffness properties. Although data sheets exist for these materials, tensile testing was carried out to give results specific to the printer and print settings that would be used to manufacture the cellular structures. For the PLA and Nylon, BS EN ISO 527-1:2019 [32] was used to calculate the properties of the material. This standard is applicable as PLA is classed as a rigid plastic with a modulus of elasticity over 700 MPa and Nylon is classed as semi-rigid as it's modulus of elasticity falls between 70 MPa and 700 MPa. The TPU was tested to BS ISO 37:2017 [33] as it is classed as a rubber material with a modulus below 70 MPa. The dimensions utilised for the tensile specimens are shown in Figures 6 and 7. The tensile specimens were printed using an Ultimaker 3 [34] and are shown in Figure 8. As the structures being analysed are made up of walls of deposited material with no infill patterns, this was replicated for the specimens. All the settings including printing temperatures were kept consistent for the specimens.

Figure 6.
BS EN ISO 527-1:2019
Dimensions (units in
mm)

Figure 7.
BS ISO 37:2017
Dimensions (units in
mm)

Figure 8.
Manufactured Tensile Specimens

Five specimens for each material were tested using a Lloyds LS5 5 kN Universal test machine, Figure 9, and displaced at 5 mm/min for PLA and Nylon and 50 mm/min for the TPU, ensuring a quasi-static loading. The samples were found to be repeatable and the average stress-strain graphs for these tests are shown in Figures 10-13. The PLA and Nylon exhibit an initial linear-elastic phase, allowing for Young's modulus (E) to be calculated. The yield stress (σ_y) of the materials was calculated using the 0.2% strain offset rule. The TPU, which is an elastomer, displays a hyper-elastic relationship and the Young's Modulus cannot be easily defined. In the FEA model, the results from the TPU tensile testing

were input into a hyper-elastic model for the material. Table 1 summaries the calculated material properties.

Figure 9. Lloyd's LS5 universal test machine

Table 1. Material properties

Material	Young's Modulus (MPa)	Yield Stress (MPa)	Ultimate Tensile Stress (MPa)
PLA	2554.5	45.3	57.4
Nylon	1457.4	34.4	40.9
TPU	N/A	N/A	36.5

During the tensile testing, the engineering stress and strain were calculated. Abaqus CAE [35] package requires the true stresses and strains of the material to be input. The true stress and strain take account of the instantaneous cross-sectional area through the tensile test. The true stress and strain were calculated using Equations 1 and 2 respectively,

$$\sigma_{true} = \sigma_{eng}(1 + \varepsilon_{eng}) \quad (1)$$

$$\varepsilon_{true} = \ln(\varepsilon_{eng} + 1) \quad (2)$$

where σ_{true} is true stress, ε_{eng} is engineering strain and ε_{true} is true strain.

For the PLA and Nylon, the materials were assumed to become plastic after the yield point of the materials. To calculate the plastic strain, Equation 3 was used.

$$\varepsilon_{plastic} = \varepsilon_{true} - \frac{\sigma_{true}}{E} \quad (3)$$

Figure 10. Stress-strain curve for the PLA material

Figure 11. Stress-strain curve for the Nylon material

Figure 12. Initial region stress-strain curve for the Nylon material

Figure 13. Stress-strain curve for the TPU material

2.3 Additive Manufacturing

The Ultimaker 3 [34], shown in Figure 14, was selected for this study due to its ability to print with dual materials. This printer uses Fused Deposition Modelling (FDM), where layers of material are deposited to build up the structure. The printer uses two nozzles which each deposit the different materials, Figure 15. In this study, the nozzles used were both 0.4 mm. As the printer creates one layer at a time, 3D printed structures often fail due to layer adhesion instead of material failure. To prevent this, all the structures were printed so that the loading was parallel to the layers. Another consequence of this dual FDM method is that it will print one material at a time. This is the most critical issue in multi-material printing as the boundary regions between the materials is often the origin for the failure point. This affinity boundary region was researched by Lopes et al. [36] where they concluded that it caused a significant performance decay. In the study, they suggested the use of mechanical interlocking systems which is possible due to the geometric freedom of additive manufacturing. It was found that the boundary joining method which offered the best performance was the use of material splicing, Figure 16, where small overlaps are made between the materials to increase the bonding surface area.

Figure 14. Ultimaker 3

Figure 15. Dual nozzles

Figure 16. Dual material splicing

The first layer of a printed structure is critical to ensure the success of the print. Manufacturers recommend different methods for each material to achieve bed adhesion however as multiple materials were used in the same print, a bed adhesion method that suited both materials needed to be found. Different methods were employed such as differing temperatures of the heated bed, PVA glue and Kapton tape. The method which provided the most success was the combination of blue painter's tape and hairspray which provided a tacky surface for the materials to adhere to.

Each material is extruded at a high temperature and as the material cools, it contracts. If the material cools unevenly then the material can warp out of shape. This is often seen as the edges of a print curling up as the outside of the print cools faster than the inside. It can also cause cracks within the structure. This effect is more evident when printing materials with a high glass transition temperature. To reduce the effect of warping an enclosure is required to prevent any air flows from cooling the print.

The heated bed should be kept around the glass transition temperature but well below the melting point of the materials. These temperatures are summarised in Table 2.

Table 2. Material temperatures

Material	Glass transition temp °C	Melting point °C	Data sheet
PLA	60	140	[37]
Nylon	50	195	[38]
TPU	-24	220	[39]

As the structures were made up of multiple materials, this meant that the nozzle was constantly stopping and starting the flow. This resulted in several challenges. Firstly, it caused strings of material to be deposited on the print, shown in Figure 17. This occurred as the unused nozzle slowly dripped melted material. To prevent this, the nozzle that wasn't being used was allowed to cool down below the melting point of the material and the material was slowly retracted by 5 mm back into the nozzle. This retraction needed to be slow as if it was too fast it would cause melted material to be pulled up the nozzle and could cause the nozzle to clog. A retraction speed of 25 mm/s was found to prevent jams from occurring. Another feature offered by the slicing software was an 'ooze shield', shown in Figure 18. This created a wall around the print which prevented the dripping material from adhering to the object. Another consequence of material switching is that the dormant nozzle loses pressure as it sits idle. To build up the pressure before the nozzle is used to print again, a prime tower was used, Figure 18. This created a small sacrificial structure away from the print which allowed the nozzle to get back up to pressure. The printer parameters used during the printing process are provided in Table 3. The manufactured structures are shown in Figures 19, 20 and 21.

Figure 17. Stringing on prints

Figure 18. Ooze shield & prime tower

Table 3. 3D printer parameters for Ultimaker Cura 4.5

Layer height	0.3 mm	Wall line count	6
Print speed (PLA)	50 mm/s	Line width	0.35 mm
Print speed (Nylon)	35 mm/s	Brim	4 mm
Print speed (TPU)	25 mm/s	Part cooling	Off
PLA temperature	195°C	Prime tower	On
Nylon temperature	260°C	Ooze shield	On
TPU temperature	240°C	Bed temperature	60°C

Figure 19. 3D printed hexagonal (honeycomb) specimens: (a) PLA (b) PLA-Nylon (c) PLA-TPU

Figure 20. 3D printed re-entrant specimens: (a) PLA (b) PLA-Nylon (c) PLA-TPU

Figure 21. 3D printed anti-tetrachiral specimens: (a) PLA (b) PLA-Nylon (c) PLA-TPU

2.4 Experimental Compression Testing of Specimens

A quasi-static compression test was carried out using a Zwick Z100 universal test machine. The additively manufactured samples were compressed between two flat compression plates with a 100 kN load cell. The structures were compressed at a rate of 10 mm/min to prevent inertial forces within the structure, therefore ensuring it was quasi-static. The samples were crushed to 85% displacement or until it was obvious the structures had completely densified. The force-displacement was extracted from each test which was repeated three times.

Figure 22. Zwick Z100 test frame

2.5 Finite Element Modelling

To analyse these complex multi-material cellular structures, an FEA modelling method was developed. The focus of the model was a quasi-static compression analysis on each of the structures, however, the majority of the model could be utilised for other loading conditions. The geometry was modelled in Solidworks 2019 [40] and Abaqus CAE [35] package was subsequently used to perform the analysis. As the structures being investigated have a constant cross-section through their depth, the structures were modelled as 2D. This reduces the computational power required to run the analysis. For the finite element analysis, a 4-node bilinear plane stress quadrilateral element (CPS4R) which has reduced integration with hourglass control was used.

The structures are made up of multiple materials meaning that many small components make up the entirety of the structure. To assemble all these components within the CAE package would be inefficient. To overcome this, the best method found was to create a Solidworks model made up of separate bodies. Each body was then either classed as 'wall' or 'corner'. All of the wall components were then exported as a DXF and imported as a sketch into Abaqus to create a single part, and the process was repeated for the corner components. As an example, the DXF's for the honeycomb geometry is shown in Figure 23.

Honeycomb Walls

Honeycomb Corners

Figure 23. Honeycomb Sketch DXF's

The interfaces between the different materials needed to be defined so that the CAE package knew where to tie components to create a bond. In a 3D analysis, this could be done automatically by utilising the tool 'Find Contact Pairs', however, this tool is not available for a 2D analysis. To define this region,

a set was created of each of the elements on the walls which would be an interface region and the same repeated for the corners. A tie constraint between these two sets was created with a spacing tolerance of 0.1 mm. This assumed a perfectly bonded interface. A global interaction property was also applied with a tangential frictional penalty of 0.2 and normal hard behaviour to ensure no penetration between the cellular walls occurred.

The top and bottom compression plates were modelled as a discrete rigid wire with the bottom plate encastered, and the top plate fixed in all directions except the vertical which moved with a constant velocity. The three FEA models for the assembled structures are shown in Figure 24.

Figure 24. FE model geometry

Abaqus Dynamic-Explicit algorithm was utilised for the study as the computational cost of this solver is less than the implicit solver however a few considerations needed to be made [41]. One of these conditions is that as the explicit solver is conditionally stable, the stable time period is much smaller than the implicit solver. This means that the time period for which the quasi-static compression takes place should be kept as small as possible for the model to be computationally efficient. A consequence of this is that the study may become more dynamic and the inertial forces within the structure will become apparent. Another method which was utilised to reduce the stable time was mass scaling [42]. This feature reduces the simulation time but again can increase the inertial forces. To ensure that the study remains quasi-static while also aiming to reduce the computational time, the kinetic energy was analysed to ensure that it stays under 5% of the internal energy of the structure.

2.5.1. Mesh sensitivity study

To ensure a suitable mesh density is utilised to provide an accurate representation, a mesh sensitivity study was carried out. A coarse, medium and fine mesh were examined, and the force-displacement graphs & energy absorption analysed to ensure convergence. Equation 4 gives a relationship between the number of elements (N) between the meshes. A refinement factor, R , of 1.5 was utilised in this study. D gives number of dimensions present in this study. As this is a two-dimensional analysis, $D = 2$.

$$N_{Fine} = R^D \cdot N_{Coarse} \quad (4)$$

Each structure: honeycomb, re-entrant and anti-tetrachiral, were analysed to ensure the mesh was sufficiently refined to provide accurate results.

Figure 25. Honeycomb mesh refinement

For the honeycomb structure, Figure 25, the fine and medium meshes both exhibit a similar deformation response, with the medium mesh slightly over predicting the energy absorbed by 4% when compared to the fine mesh. The coarse mesh however severely under-predicted the results by 93%. This was due to the coarse mesh only having a single element thickness through the wall. For the honeycomb analysis, the medium mesh will be utilised due to its reduced computational cost and accuracy of results.

Figure 26. Re-entrant mesh refinement

For the re-entrant structure, Figure 26, The medium and fine meshes both exhibit similar results between a compression of 0-42 mm. Between 42-55 mm, the two meshes exhibit slightly varied results due to variations in how the onset of the densification stage occurs. The coarse mesh over predicts the energy absorbed through the compression by 26% and the medium mesh by 7.8% when compared to the fine mesh. The fine mesh will be utilised for this study for the re-entrant geometry due to its improved prediction just prior to the densification stage as this region is critical to the total energy absorption of the structures.

Figure 27. Anti-tetrachiral mesh refinement

For the anti-tetrachiral structure, Figure 27, The medium and fine mesh both exhibit similar results through the compression however similar to the re-entrant refinement, the coarser mesh over predicts the energy absorbed by 11.7% when compared to the fine mesh. Due to the added computation time of the fine mesh, the medium mesh will be utilised as the percentage difference of 1.25% provides an acceptable accuracy.

3 Results

3.1 Results Analysis

There are three stages that occur in the compression of cellular structures: elastic, plateau and densification. A typical graph for cellular compression is shown in Figure 28. In the elastic phase, the material's compression is linear, and the structure has not experienced any yielding. During the plateau stage, the cellular structure is beginning to collapse either through plastic or elastic buckling. For the structures, we are interested in the amount of energy absorbed before the densification process takes

place. This is where all the cells have compacted and the material itself is being compressed. There are different methods of determining when this process begins, however, Li et al. [43] identified that the method of analysing the energy absorption efficiency (η), calculated using Equation 5, provides unique and consistent results, therefore this method will be utilised. The energy absorption efficiency through the compression is plotted and the peak of the graph shows where the densification is beginning, as demonstrated in Figure 29. When this graph is generated, noise is evident in the plot. To reduce this, a 6th order polynomial trend line is utilised to smooth the results.

Figure 28. Force-displacement curve for the compression phases of cellular structures

Figure 29. Energy absorption efficiency through the compression

$$\eta(\varepsilon) = \frac{1}{\sigma(\varepsilon)} \int_{\varepsilon_y}^{\varepsilon} \sigma(\varepsilon) d\varepsilon \quad (5)$$

This densification point is then transferred to the force-displacement graph where the energy absorbed before the densification phase can be calculated. The energy absorbed is equivalent to the work done by the structures, Equation 6, which is the area under the graph.

$$EA = \int_0^d F d\delta \quad (6)$$

These structures are commonly used for light-weight applications. The specific energy absorption (SEA), calculated with Equation 7, provides an indication of the energy absorbed (EA) per unit mass (m).

$$SEA = \frac{EA}{m} \quad (7)$$

The Poisson's ratio through the compression will be analysed as this indicates the geometric response of the cellular structures. To calculate this, nodes spaced evenly within the FEA structure were selected and their motion through the compression was output. The average transverse strain of all the points within the structure was then found and the Poisson's ratio was calculated using Equation 8.

$$\nu = -\frac{\varepsilon_{\text{transverse}}}{\varepsilon_{\text{longitudinal}}} \quad (8)$$

To find the displacement at which the yield in the structure occurred, the FEA model was probed to find when the von Mises stress in the material exceeded the yield point of the material calculated in the tensile tests.

3.2 Experimental Results

The results for the honeycomb compression testing of the additively manufactured samples are given in Figure 30. Three of each sample were tested to ensure repeatability. The results for the (a) PLA and (c) PLA-TPU honeycomb show that the results are repeatable with only mild fluctuations in the plateau stage. The (b) PLA-Nylon, however, shows a large variance in the results. This was due to insufficient bonding between the two materials which could not withstand the forces experienced through the compression. This resulted in the two materials separating randomly within the structure, deeming the test unrepeatable.

Figure 30. Force-displacement curves from the honeycomb specimens' compression tests: (a) PLA (b) PLA-Nylon (c) PLA-TPU

Figure 31. Force-displacement curves from the re-entrant specimens' compression tests: (a) PLA (b) PLA-Nylon (c) PLA-TPU

Figure 32. Force-displacement curves from the anti-tetrachiral specimens' compression tests: (a) PLA (b) PLA-Nylon (c) PLA-TPU

For the re-entrant testing, Figure 31, the (a) PLA and (c) PLA-TPU again show repeatable results. The (b) PLA-Nylon, however, shows a lot of fluctuation during the tests, again due to inadequate bonding. For the experimental testing of anti-tetrachiral, Figure 32, similar to the previous geometries, the (a) PLA and (c) PLA-TPU showed repeatable results however large differences were seen between the (b) PLA-Nylon. This structure showed consistent results during the elastic stage however at 15 mm the forces and rotations seen in the anti-tetrachiral structure caused the materials to pull apart and break down in a random manner.

Figure 33 shows the structures post-loading. After the compression loading was removed from the three structures, it was seen that the (a) PLA material had yielded and remained permanently deformed, the (b) PLA-Nylon had broken apart due to inadequate material bonding and the (c) PLA-TPU had not yielded and it returned to its original shape post-loading.

Figure 33. Structures after compression (a) PLA (b) PLA-Nylon (c) PLA-TPU

It was shown that the manufactured samples for the three structures; honeycomb, re-entrant and anti-tetrachiral were repeatable for the PLA and PLA-TPU materials. The PLA-Nylon structures however

were deemed unrepeatable due to the random nature of their compression caused by the two materials separating prematurely. It was found that the rotations between the two materials occurred in the splicing interfaces which were defined by the bonding and not the material's properties.

3.3 Numerical Validation

To ensure that the deformation modes in the compression of the structures occurred in the same manner between the Finite Element Analysis (FEA) and experimental testing, images were taken throughout the compression at different displacements. From Table 4, it can be seen that the deformations are similar between the FEA and experimental compression. The collapse in the PLA and PLA-TPU structures occurs in a different layer of cells however the deformation of these cells is consistent between the tests. Table 5 shows that the deformation patterns for the re-entrant correspond well between the experimental and FEA compressions. At a compression of 10 mm for the PLA, the experimental image shows that the vertical walls begin to rotate, a phenomenon not seen with the FEA which is likely due to imperfections in the 3D printed structures causing anisotropy in the material. In the PLA-TPU material, this is also seen at 20 mm. At 20 mm in the PLA the cell collapse occurs in different cell layers however the deformation of these cells is consistent. At 50 mm in the PLA, some differences are exhibited between how the walls collapse, caused by discrepancies during the onset of densification. From Table 6, it is shown that the PLA and PLA-TPU anti-tetrachiral deformation pattern matched well between the FEA and experimental however the PLA-Nylon does not as the experimental test began to break down after 20 mm due to separation of materials. In the PLA deformation, it is shown that bending occurs in the connecting walls to allow for the rotation of the tangential rings, however, in the PLA-TPU these walls remain straight as the flexible connecting joints allowed rotation.

Table 4. Honeycomb deformation patterns comparison

Compression	PLA		PLA Nylon		PLA TPU	
	FEA	Experimental	FEA	Experimental	FEA	Experimental
0mm
10mm
20mm
30mm
40mm
50mm
60mm

Table 5. Re-entrant deformation patterns comparison

	PLA		PLA Nylon		PLA TPU	
	FEA	Experimental	FEA	Experimental	FEA	Experimental
0mm
10mm
20mm
30mm
40mm
50mm
60mm

Table 6. Anti-tetrachiral deformation patterns comparison

	PLA		PLA Nylon		PLA TPU	
Compression	FEA	Experimental	FEA	Experimental	FEA	Experimental
0mm
10mm
20mm
30mm
40mm
50mm

Figure 34. Comparison of experimental and FEA values for the honeycomb materials: (a) PLA (b) PLA-Nylon (c) PLA-TPU

Figure 34 shows a comparison between the three materials for the honeycomb structure. The results for the FEA models match well with the experimental values for (a) PLA and (c) PLA-TPU however for the (b) PLA-Nylon, the FEA predicted a higher amount of energy absorption. It is seen in the region of 0-7 mm, the elastic phase, the results correspond well however the FEA then predicted a higher peak value. In the (c) PLA-TPU, the FEA model predicted a smoother plateau phase than the experimental results, likely caused by inconsistencies in the additively manufactured samples.

Figure 35. Comparison of experimental and FEA values for the re-entrant materials: (a) PLA (b) PLA-Nylon (c) PLA-TPU

The results for the Experimental and FEA match well for (a) PLA and (c) PLA-TPU for the re-entrant, shown in Figure 35. In the (c) PLA-TPU in the region 34 to 44 mm, the experimental test showed a large spike in the force which is not seen in the FEA. This phase of the compression is where the materials are beginning to densify and is very dependent on the direction the wall collapse. Figure 36 illustrates this, as it can be seen the walls collapse in different directions. Again, the PLA-Nylon showed differing results.

Figure 36. Re-entrant PLA comparison at 45 mm (a) FEA (b) Experimental

Figure 37. Comparison of experimental and FEA values for the anti-tetrachiral materials: (a) PLA (b) PLA-Nylon (c) PLA-TPU

In Figure 37, The FEA of the anti-tetrachiral has been shown to match well with experimental results for the (a) PLA and (c) PLA-TPU. The (c) PLA-TPU shows a different gradient to the densification stage however this region is not used for the calculation of the energy absorbed. The (b) PLA-Nylon showed differing results due to the experimental structure breaking apart.

Table 7 shows a comparison for the energy absorption between the FEA and experimental tests. It is shown that the FEA over-predicts the results however, for both the (a) PLA and (c) PLA-TPU this difference is below 8% in all cases and is deemed acceptable. A few aspects of this study may have caused these discrepancies. The 3D FDM printing process causing imperfections within the structure as it is not a consistent process. These imperfections include warping due to cooling of outer layers, gaps between extrusion lines, temperature variations and inconsistent extrusion. Although steps were taken to minimise these issues, some inconsistencies remain. The process of laying down extrusion lines also creates anisotropy within the structures whereas the FEA model assumes the material is perfectly isotropic. Another aspect that may have caused the over-prediction was the assumptions made during the study which include assuming a perfect bond between the material affinity boundaries.

Table 7. Comparison of energy absorption values between the FEA and experimental tests

Structure	PLA		PLA-Nylon		PLA-TPU	
	Exp (J)	FEA (J)	Exp (J)	FEA (J)	Exp (J)	FEA (J)
Honeycomb	783	805	210	428	113	118
Re-entrant	1098	1185	332	583	196	210
Anti-tetrachiral	1260	1326	373	962	479	456

3.4 Comparison between materials

Figure 38-Figure 40 compare the different materials used in each structure for the honeycomb, re-entrant and anti-tetrachiral respectively. Across the three structures, it was found more flexible materials are introduced into the structure it reduces the force required for compression. Due to the different materials, the phases of the compression occurred at different points during the compression; characterisation of these phases are explained in Section 3.1. In the honeycomb, the elastic phase for the PLA material occurs between 0-7 mm and in the PLA-TPU it occurs between 0-12 mm. This characteristic is also seen in the re-entrant and anti-tetrachiral. By introducing a material with a lower stiffness into the corners of the structure, it therefore extends the elastic phase.

Figure 38. Force-displacement comparison of honeycomb structures

Figure 39. Force-displacement comparison of re-entrant structures

Figure 40. Force-displacement comparison of anti-tetrachiral structures

The plateau stage also differs with the PLA showing large fluctuations and the PLA-TPU having a smooth plateau stage. This is due to the characteristics of the compression. During the compression of the PLA, the structure deforms with buckling in the walls and plastic yielding in the corners. The PLA-TPU however deforms through elastic deformation in the corners only.

Figure 41 shows the instantaneous Poisson's ratio of each structure throughout the compression and Table 8 gives the peak and average Poisson's ratio of the structures. This was calculated on the FEA tests using the method described in Section 3.1. This provides an insight into the process of the compression in the structures.

Figure 41. Poisson's ratios through compression comparison: (a) Honeycomb (b) Re-entrant (c) Anti-tetrachiral

Table 8. Average and peak Poisson's ratio values of the materials with different geometries

	PLA		PLA-Nylon		PLA-TPU	
	Average	Peak	Average	Peak	Average	Peak
Honeycomb	0.062	0.219	0.078	0.277	0.091	0.212
Re-entrant	-0.089	-0.135	-0.077	-0.118	-0.095	-0.130
Anti-tetrachiral	-0.188	-0.356	-0.133	-0.214	-0.208	-0.317

In the (a) honeycomb geometry it is seen that the PLA had an initial Poisson's ratio of 0.219 but this began to fall rapidly and converges to a ratio of 0.03, with an average value of 0.062. In the PLA-TPU honeycomb, the initial value is lower at 0.212 but throughout the compression, the structure maintained a higher Poisson's ratio when compared with the PLA leading to a higher average Poisson's ratio of 0.091.

In the (b) re-entrant structure, the materials had a similar initial value of approximately -0.07. The Poisson's ratio then decreased at a different rate across the materials during the elastic phase of compression but all peak at a similar value. After the elastic phase, the ratio in the PLA increased rapidly to a value of -0.05 whereas in the PLA-TPU the Poisson's ratio only increases to a value of -0.115 and

the low Poisson's ratio is sustained through the plateau stage. This results in an average Poisson's ratio of -0.089 in the PLA and -0.095 in the PLA-TPU.

It is shown in (c) anti-tetrachiral that the Poisson's ratio follows a similar pattern between the structures, and all have a similar average Poisson's ratio through the compression of -0.207.

In summary, for the honeycomb structure, by introducing a material of a lower stiffness in the corners, the average Poisson's ratio through the structure is increased. For the re-entrant structure, a lower average Poisson's ratio is achieved, showing the auxetic effect can be maximised by hinging the corners of the structure. In the anti-tetrachiral, the use of differing stiffnesses does not affect the Poisson's ratio.

When comparing the densification point; which was identified using the energy absorption efficiency method explained in section 3.1, it was shown that it occurs at different displacements. Figure 42 shows these densification points across different structures and materials.

Figure 42. Densification points of structures

A lower Poisson's ratio causes the structures to densify earlier as the material is pulled into the core of the structure, in contrast with the positive Poisson's structures where the material spreads away from the centre. It is shown in the re-entrant structure that the densification occurs earlier in the PLA-TPU when compared with the PLA. This corresponds with the decrease in average Poisson's ratio as previously shown. In the anti-tetrachiral structure, the densification point only changed by 0.9 mm between the PLA and PLA-TPU which corresponds with the constant Poisson's ratio across the structures. In the honeycomb structure, the densification point occurred later in the compression from the PLA-TPU which coincides with the increase in average Poisson's ratio.

Figure 43. Total specific energy absorbed to densification

The total specific energy absorbed of each structure is provided in Figure 43. This is the energy absorbed up until the densification point. It is shown that the single (a) PLA material provides the highest amount of energy absorption across all three structures when compared with the (b) PLA-Nylon and (c) PLA-TPU structures. The (a) PLA anti-tetrachiral absorbed the most energy of all the structures, absorbing 65% more energy than the honeycomb and 12% more than the re-entrant. In the (c) PLA-TPU, the anti-tetrachiral again performed the best, however in this structure it absorbed 163% more than the honeycomb and 77% more than the re-entrant.

As shown in Figure 33, during the compression of the structures, the PLA-TPU structures did not yield and once the compression load was removed, they returned to their original pre-compression shape. This was not seen in the PLA and PLA-Nylon structures. The yield points, which are shown in Table 9, were taken as the point in the simulation where the yield (von mises) stress of the material. Absorbed energy amounts until yield are calculated regarding these yield points.

Table 9. Yield points of the structures during compression (in mm)

	(a) PLA	(b) PLA Nylon	(c) PLA-TPU
Honeycomb	6.7	7.9	62.9
Re-entrant	12.4	13.2	44.0
Anti-tetrachiral	7.6	9.4	42.0

Figure 44. Total specific energy absorbed to structure yield

Figure 44 shows a comparison between all the structures for the energy absorbed up until the point where the structure yields. It is seen that the (c) PLA-TPU structure absorbs more energy than the (a) PLA and (b) PLA-Nylon for the auxetic structures; re-entrant and anti-tetrachiral. The honeycomb sees an increase from 58 to 118 kJ/kg, a 103% increase between the (a) PLA and (b) PLA-TPU, the re-entrant, an increase from 116 to 221 kJ/kg, 90.5% increase and the anti-tetrachiral 87 to 292 kJ/kg, a 235% increase. Of the three structures, for the PLA-TPU, the anti-tetrachiral structure absorbed 147% more energy than the honeycomb and 32% more than the re-entrant. This occurs because in the compression of the (a) PLA and (b) PLA Nylon, after the initial elastic phase, the structures collapse under plastic buckling of the material during the plateau stage however in the (c) PLA-TPU it collapses through elastic buckling due to the elastomer corner joints. As the majority of the energy is absorbed during this plateau stage of compression then by ensuring no yielding takes place in this region, the energy absorbed by the structure can be increased. For the (a) PLA & (b) PLA-Nylon, it is seen that the re-entrant absorbs the most energy before yielding. This is due to the elastic phase of compression lasting the longest in the re-entrant in comparison with the other structures before plastic deformation occurs.

The two comparisons; to the densification point and to the yield of the structure, show that if a single loading cycle of the structure is required, for example a crash-worthy structure, then the single material structures provide the best energy absorption properties, with the anti-tetrachiral absorbing the highest amount of energy at 1326 kJ/kg. However, if repeated loading cycles are required, where the material does not yield during the compression, the dual-material structure of PLA-TPU provides

the highest amount of energy absorption in the anti-tetrachiral structure with 292 kJ/kg being absorbed compared with 116 kJ/kg for the single material re-entrant.

4 Discussion

4.1 Applications

In this study, it was found that by introducing an elastomer material into specific regions of the auxetic structure, it provides an increased amount of energy absorbed when repeated loading is required as yielding in the structure is prevented. This provides an interesting opportunity for these structures to be developed for spring applications. Spring platforms or sheets could be made using these structures, which could be used for machine vibration isolation, exercising mats for high-performance sports, sporting shoes or any application that requires repeated energy absorption. These examples can be increased depending on the needs. The main idea is, using auxetic dual materials is a good choice or at least an alternative for that kind of applications.

Due to current manufacturing constraints, the use of multiple materials within a single structure is difficult to achieve without costly production processes. Currently, the only way to produce these structures is through additive manufacture which is only suitable for prototyping and specialist applications. This is due to the long manufacture times of parts when compared to processes such as injection moulding. This may be improved in the future as the speed of additive manufacturing increases. However, as most auxetic structures have a consistent cross-section through its depth, they could be manufactured using extrusion moulding. To achieve the dual materials, the outer material which would be the material with a lower stiffness could be extruded in a sheath form and the stiffer wall material extruded separately. The wall material could then be coated in an adhesive and pressed into the sheath. An initial 3D printed concept was created to test this sheath design, shown in Figure 44.

Figure 44. Sheath Multi-Material Structure

4.2 Future Studies

To begin development of these structures some further studies would be required. As this study only focused on quasi-static loading, different loading conditions would need to be investigated such as impact loading. Another study could focus on the vibration isolation and force transmissibility of these structures. This study did not consider fatigue loading of these structures, which would be required if the structures were going to experience multiple loading cycles. The effect of varying the wall thickness, proportions of materials, the materials themselves or the geometry of the auxetic cells should also be investigated to see how they affect the stiffness and to optimise the energy absorption properties of the structures. This study also only investigated two auxetic geometries; re-entrant and anti-tetrachiral. Future studies could investigate the effect of using dual-materials on auxetic geometries such as double arrowhead, rota-chiral or star-shaped.

4.3 Multi-Material Adhesion

In this study, it was found that the bonding between the PLA-Nylon was insufficient to withstand the forces required during the compression. For the material combination to be utilised in future studies, the bonding between the materials would need to be improved. This could be achieved through modifications to the geometry of the interface which could include a mechanical interlocking joint to prohibit the materials pulling apart. Another opportunity is the modification of the materials to allow improved bonding. Companies such as Henkel Adhesive Technologies [44] are currently working on adding adhesive additives to plastic filaments. This is aimed at improving layer adhesion during the FDM printing process however it may also provide improvements for material bonding. Stratasys have developed a 3D printer which uses PolyJet technology, the Connex 3 [45], which uses several base resins which can be blended to create digital materials. This creates a transitional interface between the two materials meaning there is no distinct boundary which causes a stress concentration region.

5 Conclusions

To analyse dual-material cellular structures, a quasi-static compression FEA model was developed using Abaqus Dynamic-Explicit solver. A process of setting up the analyses for complex multi-material geometries in an efficient manner was created. The results were validated through a comparison with additively manufactured experimental testing under the same loading conditions.

It was shown that, for the situations where single loading cycles were required, for example, for crashworthy structures, the single material structures offered the highest performance where they absorbed the largest amount of energy. If multiple loading cycles are required, the multi-material structures offer the best solution. It was also found that through introducing materials with varying

stiffnesses into specific regions within the structure, the Poisson's ratio through the compression could be tailored.

In Poisson's ratio analysis, for the honeycomb (non-auxetic) structure, by introducing a material of a lower stiffness in the corners, the average Poisson's ratio through the structure was increased. For the re-entrant structure, a lower average Poisson's ratio was achieved, showing the auxetic effect can be maximised by hinging the corners of the structure. For the anti-tetrachiral structure, the use of differing stiffnesses did not affect the Poisson's ratio.

By introducing an elastomer which has low stiffness and high failure strain into specific areas in the structure and creating a dual material cellular structure, the plateau stage of the compression can be made to occur through elastic buckling. In a single material plastic structure, the plateau region occurs through plastic buckling. This plastic buckling allows for a higher amount of energy absorption however the structure is permanently deformed and cannot be reloaded. Through the introduction of materials with a lower stiffness into specific regions within the honeycomb, re-entrant and anti-tetrachiral architecture, the elastic phase of the compression can be extended.

For the requirement of a high energy absorption structure with a single loading cycle such as a crash-worthy structure, the single material PLA anti-tetrachiral structure provided the most energy absorbed up until the densification point of the structure. This demonstrates that, for the selected architectures, auxetic structures absorb a higher amount of energy when compared with a non-auxetic structure.

For the requirement of high energy absorption with multiple loading cycles, where the structure does not yield, the PLA-TPU anti-tetrachiral structure provided the highest energy absorption. This demonstrates that, for the selected architectures, if multiple loading cycles are required, the multi-material auxetic structures offer the best solution.

Multi-material structures add further characteristics which can be specified to meet different design requirements. These characteristics include material selection and the proportion of the two materials within the structure.

Declaration of conflicts of interest

The authors declared that they have no conflicts of interest in this work.

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CRediT authorship contribution statement

Ross Johnston: Investigation, Data curation, Software, Visualization, Validation, Writing - original draft.

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