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On the design workflow of auxetic metamaterials for structural applications

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Abstract

Auxetic metamaterials exhibit an unexpected behaviour of a negative Poisson's ratio, meaning they expand transversely when stretched longitudinally. This behaviour is generated predominantly due to the way individual elements of an auxetic lattice are structured. These structures are gaining interest in a wide variety of applications such as energy absorption, sensors, smart filters, vibration isolation and medical etc. Their potential could be further exploited by the use of additive manufacturing. Currently there is a lack of guidance on how to design these structures. This paper highlights state-of-the-art in auxetic metamaterials and its commonly used unit-cell types. It further explores the design approaches used in the literature on creating auxetic lattices for different applications and proposes, for the first time, a workflow comprising design, simulation and testing of auxetic structures. This workflow provides guidance on the design process for using auxetic metamaterials in structural applications.

Keywords: auxetics, metamaterials, lattice, design workflow, negative Poisson's ratio.

1. Introduction

Metamaterials are materials which have been engineered to have properties that do not tend to be found in naturally occurring materials. Often these take the form of improved mechanical properties that allow performance advancements in various applications to be realized [1]. These material properties are usually tailored through modification of geometry [2] rather than relying on the bulk behaviour of material they are composed of.

Auxetic materials are a set of metamaterials that exhibit a negative Poisson's ratio or 'NPR'. What this means is that when these materials are placed under tension and stretched, they also expand laterally, and vice versa. This is a novel behaviour, as conventional materials contract laterally when placed under tension. Figure 1(a) illustrates this difference in behaviour.

There are some natural materials which have been shown to exhibit auxetic behaviour, examples include cancellous bone in the human tibia, cat skin, and cow teat skin [3]. However, auxetic materials used in applications tend to be metamaterials that get their auxetic nature through an engineered geometric structure, as these can be modified for a design and manufactured.

While there are exceptions [4], the majority of manufactured auxetic materials take the form of repeating cellular structures/lattices. As a result, this paper will only focus on auxetic materials that are made of repeating cellular structures. These structures can be on the micro-scale, as is the case of auxetic foams [5], or on the macro-scale as is often the case with additively manufactured (AM) structures. AM has become a popular technology for manufacturing auxetic structures due the ease of customising part geometry. As such, this paper references multiple manufacturing methods but is focused on designing structures manufactured by AM.

A unit cell is the smallest portion of a lattice that describes the repeating structure of the entire lattice. Figure 1(b) shows an example of a common auxetic bowtie shaped unit cell in the literature and demonstrates how the geometry of the cell leads to auxetic behaviour. When placed under tension the re-entrant cell acts like a combination of struts and hinges, deforming into a more rectangle like structure that expands laterally to the force. The mechanism required for auxetic behaviour mainly depends on the geometric pattern, and as such the same unit cells can be repurposed for applications with different scales and materials.

The unusual deformation behaviour of auxetic structures has been linked to a number of desirable properties [3]; these include:

- Improved shear resistance [6];
- Indentation resistance [7];
- Fracture resistance [8];
- Synclastic behaviour [9];
- Variable permeability [10];
- Better energy absorption/impact resistance [11,12].

The desirable properties of auxetic materials have led to them being developed for use in several applications, a selection of which can be seen in Figure 2. The applications shown here cover a wide range of industries, from medical, to structural, to sportswear and aerospace. All these potential applications rely on auxetic properties in a different way, highlighting the need for a design process that can be used to incorporate auxetic structures into a developed application. Further details of these applications and the benefits auxetics bring to them are in Section 4.

Currently in the literature a vast majority of the studies focus on examining auxetic structures predominantly through numerical modelling and lab testing. While they contain useful information for those wishing to develop an end-use application, they often do not go beyond the lab testing phase. This is likely due to the low technology readiness level of auxetic designs and the lack of a proper design workflow.

To the best of authors' knowledge, there is no workflow available in the literature for design of auxetics for different applications. This paper outlines what auxetic metamaterials are and the benefits they provide over conventional materials. An investigation is then performed into previous research around the design and manufacture of auxetic metamaterials for a variety of applications. This is done to determine a standard design workflow for applications that can benefit from auxetic materials. Gaps in the current literature around the design process are also identified.

Each section will explain a different set of core concepts from the point of view of how they apply to the design for an application. A brief overlook of the sections is as follows:

Properties of auxetic structures: The superior properties of auxetics and how they may benefit applications.

Applications: A selection of previous applications and how auxetic structures have benefitted and been incorporated into the design.

Types of auxetic cell geometries: The different types of auxetic unit cells, how cells affect the mechanical properties of a structure, guidelines on how to choose a cell and how to design a cell for a specific application.

Manufacturing methods and material selection: Known methods for manufacturing auxetic structures. How selecting a manufacturing technique and material fits into the design process.

Characterisation tests: How to validate a design and collect the data required for optimising it.

Design workflow: Brings the learning from the previous sections together to create a general process for the design of auxetic structures.

Other considerations: Any additional considerations which are not part of the standard design workflow.

Gap analysis: Anything currently lacking from the design process that may be addressed in future research.

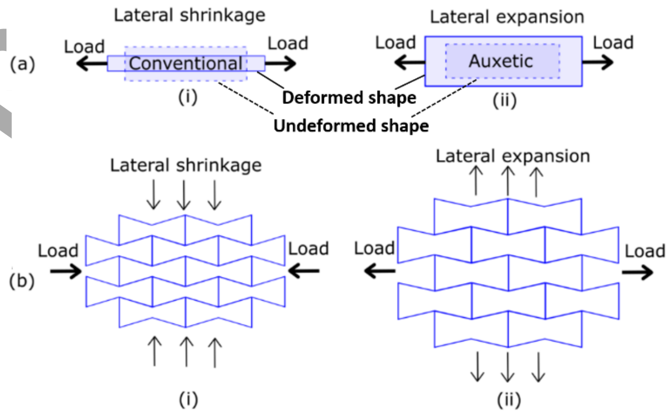


Figure 1. (a) Comparison of deformation behaviour in response to tensile loading: (i) lateral shrinkage for conventional (non-auxetic) material and (ii) lateral expansion for auxetic material; (b) Deformation mechanism of auxetic cells in response to: (i) compressive load and (ii) tensile load; bold arrows show the load direction and non-bold arrows show shrinkage direction.


(a)
(b) Balloon
Auxetic Stent undeformed
10 mm
Stent Radially expanding
Longitudinal Expansion
Inflated Balloon
Expanded Auxetic Stent
(c)
5mm
(d)
Clamp
Sample (auxetic)
Piezo
Output Wires
(f)
Conformable attachment
unfold
fold
(g)
(h)
(i)
(e)
Material concentration
Material flow direction
Material flow direction

Figure 2. Examples of applications for auxetic metamaterials: (a) Hip stem implant made with a combination of auxetic and conventional metal-biomaterials [13]; (b) Auxetic stent; Top: Mounted on balloon catheter; Bottom: Expanded by balloon catheter (in both radial and longitudinal directions) [14]; (c) Smart filter that takes advantage of the variable permeability of auxetic cells when under tension [10]; (d) Strain vibration energy harvester has increased power output due to auxetic substrate structure [15]; (e) Improved blast/impact response of auxetic sandwich panel after drop weight impact test [16]; (f) Stretchable capacitive strain sensor uses auxetic layer to improve gauge factor [17]; (g) Morphing aerofoil design that can change its shape and thus aerodynamics, it is proposed that this can improve flight efficiency at different speeds [18]; (h) Sandwich structure undergoing three-point bend test [19]; (i) Light-weight cellular vibration isolation base [20].

2. Properties of auxetic structures

2.1. Structural Level Properties

Structural material properties are the properties that an auxetic lattice exhibits at a macro level as opposed to the properties and behaviours that can be observed at a cellular level. Cellular level properties and behaviours are covered in subsection 2.2.

This section does not list all the structural properties of auxetic structures but lists the properties of auxetics that are commonly cited as being improved when compared to their conventional counterparts. When looking at design for end-use applications, it is important to consider how the benefits of auxetic structures may apply to the application requirements. The properties associated with auxetic structures can broadly be broken down into two separate categories.

There are properties that arise due to the very definition of auxeticity, meaning they can be directly linked to the structure having a negative Poisson's ratio and are not usually found in conventional structures. They directly depend on the unique deformation mechanism of auxetic structures and because of this performance is largely geometry based rather than material based. Here, these will be referred to as primary properties, see Figure 3. There are other properties that the deformation mechanism of auxetic structures can be shown to benefit, either through theory or experiments. These properties can be found in conventional structures but are expected to be improved using auxetics. These properties tend to be material and geometry based, requiring careful consideration of both for optimisation. These will be referred to as secondary properties. More detail on these properties is presented in the following subsections.

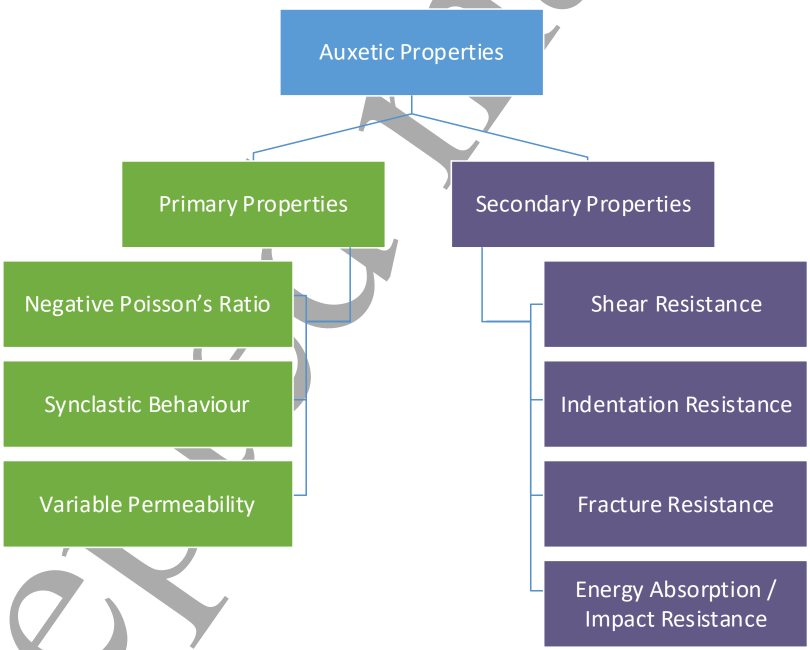


Figure 3. Primary and secondary properties of auxetic structures.

2.1.1. Synclastic behaviour

When a sheet of conventional material is bent out of plane it forms a saddle shape (anticlastic curvature.) When a sheet of auxetic material is bent out of plane it instead forms a dome shape (synclastic curvature) [21] (see Figure 4). Any auxetic unit cell will exhibit this behaviour, but some are more resistant to out of plane bending than others. The natural tendency of auxetic structures to form a dome shape is thought to aid conformability around domed surfaces.

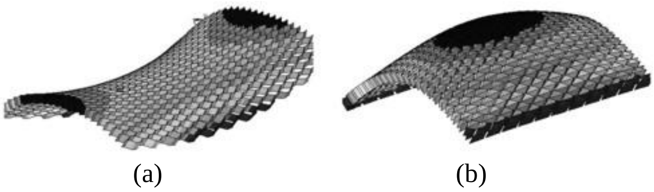


Figure 4. Out of plane bending of (a) conventional structure (saddle shape); (b) auxetic structure (dome shape) [22].

These include many natural shapes such as the human body, and auxetic structures have been looked at for sporting applications due to this increased conformability [23]. It is likely that conforming better to a shape during an impact would also help with energy absorption during an impact, furthering the potential benefits of this property [23].

2.1.2. Variable permeability

When auxetic structures are placed under tension they expand in the transverse direction. The expansion of the geometric structure also leads to the expansion of pores in the geometric structure, this mechanism can be seen in Figure 5. This means that by controlling the in-plane strain on an auxetic structure the permeability can also be controlled. This may allow the maximum allowable particle size to be controlled, or the rate of fluid flow [10,24].

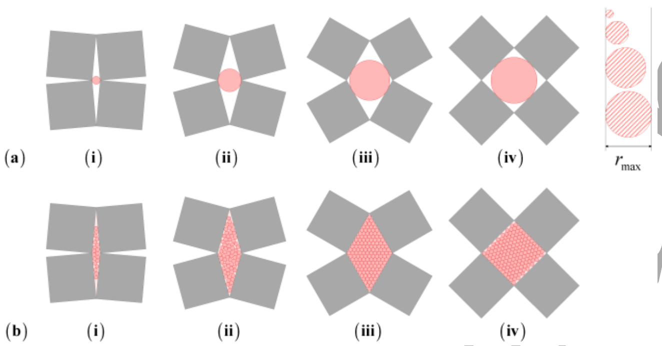


Figure 5. Variable permeability of auxetic structure under strain. (i) shows the structure at minimum strain, (iv) at maximum [24].

It should also be noted that a side effect of this porosity in auxetic structures means that they can provide an advantage in applications that require breathability (such as apparel). It also means that auxetic structures themselves cannot be relied on to be airtight or watertight, though this limitation can be dealt with by layering the structure with other material.

2.1.3. Shear resistance

Auxetic structures have been examined and analysed for their potential to demonstrate improved shear modulus when compared to conventional structures [6,25] such as a hexagonal honeycomb structure.

This evidence is supported by elastic theory which states that isotropic materials can have their properties described by four elastic constants, Young's modulus (E), shear modulus (G), bulk modulus (K), and Poisson's ratio (ν) [2]. In isotropic materials these constants are related by the equations below:

$$G = \frac{E}{2(1+\nu)} \quad (1)$$

$$K = \frac{E}{3(1-2\nu)} \quad (1)$$

What Equation 1 shows is that as $\nu \rightarrow -1$, $G \rightarrow \infty$. When combined with Equation 2 this supports the idea that as auxeticity increases so should shear resistance relative to compression resistance. It should be noted that some auxetic structures are isotropic whereas others are anisotropic.

2.1.4. Indentation resistance

Figure 6 illustrates how auxetic materials respond when subjected to indentation compared to conventional materials. In the case of non-auxetic material, the indentation causes the material below the point of contact to spread away from the contact force, allowing a deeper indentation [7]. As seen in Figure 1 auxetic materials contract when under compression. This leads to the auxetic indentation response seen in Figure 6 where material contracts below the point of contact, the greater density of material now under the indenting force resists it [26].

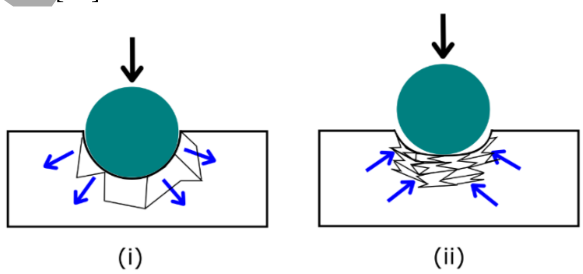


Figure 6. Deformation profile of (i) non-auxetic material and (ii) auxetic material.

2.1.5. Fracture resistance

Auxetic structures have demonstrated improved fracture resistance when compared to conventional materials. This has been demonstrated in the works of Choi and Lakes that compare mechanical performance of auxetic and conventional foams [6,8]. Fracture toughness of auxetic foams was found to be enhanced by 80% to 130% for different permanent volumetric compression ratios. Other studies have also shown that more energy is required to propagate a crack in an auxetic laminated structure [27]. It has been theorised that the fracture toughness of auxetic materials can be explained by their basic definition of having a negative Poisson's ratio. When placed under tension, the cells in an auxetic structure undergo an expansion meaning that when a crack is formed the cell expansion tends to close it, hence limiting crack propagation [28]. This effect is likely scale dependant and varies with cell size, however additional experimentation would be required to confirm this.

2.1.6. Energy absorption/impact resistance

When it comes to energy absorption, auxetic materials have reportedly improved performance compared to conventional structures. This has led to potential applications in shock absorption and vibration isolation [11,12,29–31]. Auxetic materials are also found to have improved impact resistance properties [16,32], likely partially due to the indentation resistance properties outlined earlier. Researchers have tried to add modifications to classic auxetic structures to improve their properties. For example, Chen et al. [33] added some ribs to a classic re-entrant cell and showed the enhanced energy absorption, stiffness, and strength parameters of the structure.

Multiple studies looked at the performance of auxetic panels under the effect of impulse loadings, such as blast loadings. Imbalzano et al. [11] have done a numerical study of auxetic composite panels placed under blast loading. For this study parametric analyses was performed to analyse different designs of panels and their suitability for the application when compared to conventional panels. The study showed an increase in energy dissipation and displacement reduction of the loaded auxetic panels. Qi et al. [16] have performed a numerical study and practical experiment showing the impact/blast response of auxetic honeycomb panel structures with similarly positive results.

Low energy impact responses have also been investigated. Low energy impact response on an auxetic composite has been examined by Jiang and Hu [12]. They showed that auxetic and conventional composites were both strain rate sensitive, and that the auxetic composite had greater energy absorption in the medium strain range. Yang et al. [32] fabricated auxetic sandwich panels and tested them for use in low energy impact applications. Vibration damping response of auxetic cellular structures have been examined by Zhang and Yang [20]. The auxetic structures were found to have a superior vibration damping response at a lower weight than conventional structures.

2.2. Cellular Level Properties and Behaviours

Subsection 2.1 described the structural properties that auxetic structures are known to be beneficial for but altering the design of a unit cell can also change other mechanical properties and behaviours of an auxetic structure. Furthermore, some properties depend on the geometric shape of the unit cell and have no or limited influence from the material it is made of, while other properties depend largely on both material and geometry. In the rest of this sub-section, mechanical properties and behaviours of an auxetic lattice that can be modified by adjusting a unit cell's geometry and material are listed.

For auxetic structures made of a single material, there are some mechanical properties that depend almost solely on the geometric structure:

Negative Poisson's ratio: the property that defines the level of auxeticity. This is only dependant on the cell geometry when the deformation is bending dominated. This leads to the effective Poisson's ratio having negligible dependence on the underlying material's Poisson's ratio. [34]

NPR vs strain: For many cells the quoted NPR only holds true for small strains. In reality, the NPR usually varies with strain. How NPR changes with strain depends on the unit cell type and geometry.

Auxetic strain range: Following on from the NPR vs strain property, there is typically a limit of strains for which a unit cell shows auxetic behaviour. Take the re-entrant hexagon structure in Figure 7 for example. With enough tensile strain, the structure folds out fully to become a rectangle, and stops showing auxetic behaviour. With enough compressive strain, the internal tips will touch, preventing further auxetic cell motion.

Isotropy/anisotropy: How differently the cell reacts when loaded in various directions. Some cells behave in an isotropic manner, at least when loaded in specific orthogonal directions. However, many auxetic cells are highly anisotropic and may only show auxetic behaviour in certain loading directions. Poisson's ratio for isotropic materials is bounded by the theoretical limits $-1 \leq \nu \leq 0.5$ [3]. Materials being anisotropic allow for Poisson's ratios outside of these limits to exist. This gives structures a higher theoretical NPR limit, making anisotropy beneficial in some applications.

Unit cell motion: Knowing how the unit cell moves when loaded to produce the auxetic effect is vital for certain applications such as smart filters. But it is also useful knowing how the cell might fail or where stress concentrations are. Unit cell motion can also affect how material properties change the auxetic behaviour. Ren et al. [35] found a loss of auxetic behaviour when changing the base material of an auxetic structure from elastomer to metal. Experiments were performed on 3D printed metallic auxetic structures to investigate the cause of this phenomenon. Brass was chosen as the material due to its high ductility. It was found that the buckling-induced auxetic structures lost auxetic behaviour due to the localization of plastic strain. What this shows is that although the auxetic deformation behaviour of most unit cells is thought to be independent of the base material, this does not hold true for buckling-induced structures.

Note that although the theoretical limits of these properties are determined by cell geometry, the practical limitations may be bounded by the material of the cell. For example, the full theoretical strain range of a unit cell might not be obtained if the material fails or plastically deforms due to being under high stress. There are other properties that are influenced by both material and geometry of the structure:

Young's modulus: Stiffness of the structure when put under stress.

Topology: Topology of a unit cell can have a significant influence on the NPR of the unit cell. Topology of a unit cell generally means the predefined connectivity of cell struts or, the geometry obtained by computational tools performing topology optimisation of a continuum to achieve optimal material layout. Structural topology optimisation is generally used in the industry for lightweighting applications, however, topology optimisation for auxetics is not available in commercial software packages.

Size: The size of an auxetic unit cell and its individual elements such as struts can influence several properties of the entire lattice. For example, changing a particular strut cross-section will alter the unit cell stiffness, weight, allowable strain to fracture, and NPR in a certain direction. Similarly, changing the cell size can have an impact on the mentioned properties as well as the end-use application. For example, size of a lattice unit cell may vary its efficiency in energy absorption or filtration applications.

Density: Density is mass per volume of the structure which depends on the density of the material itself and the volume it occupies in the unit cell bounding box. This also directly relates to the volume fraction (also called porosity or relative density) of the unit cell. Properties of structures are often compared based on their relative density which is defined as ρ/ρ_m where ρ is the density of the unit cell and ρ_m is the density of material it is made from. Density of a unit cell dictates the overall stiffness of the lattice. This can form the requirement of a structural application where weight and energy absorption are of importance. For applications such as auxetic filters, density can define the filtration effectiveness.

Elastic limit/Ultimate tensile strength: Stress limitations of a unit cell are influenced by both properties of the material used and the geometric cell structure. The geometry of a unit cell determines where stress concentrations form and so affects the mechanical limits of the structure.

Modifying the geometric cell structure can also allow for a different maximum elongation before failure of the auxetic meta-material.

Fatigue resistance: How susceptible the structure is to failure from cyclic loading. This depends on the unit cell motion, loads and the material used.

How much these properties are influenced by the geometric structure or the material used will depend on which unit cell is used.

3. Types of auxetic cell geometries

Designed auxetic structures will usually use unit cells that are copied from previously known patterns within the literature. New unit cells may also be identified using methods such as the Eigen mode analysis of simple shapes outlined in the work of Körner et al. [36].

Auxetic unit cells can be classified by their geometries or the deformation mechanism of the cells. They are most commonly sorted into three basic categories: re-entrant, chiral, and rotating rigid shape unit cells. The following sub-sections include a description of each unit cell type and tables listing some common cells taken from the literature, along with design notes, properties, and applications.

When a unit cell is chosen, the geometric characteristics can be tailored to optimise it for certain properties. Take the 2D re-entrant honeycomb in Figure 7 for example. The re-entrant angle is θ, h/l is the cell rib length ratio, and w is the thickness of the ribs. Here are some possible ways that the properties have been found to change when the geometric characteristics are modified:

- Increasing the re-entrant angle θ increases auxeticity and decreases the stiffness of the structure [37]. Another thing to note is that using a negative value for θ turns the re-entrant hexagon into a conventional hexagon without auxetic behaviour.
- Increasing cell rib length ratio h/l increases auxeticity up to an optimum value of 0.5, at which point it decreases again [37].
- Reducing vertical rib thickness reduces stiffness in the y direction E_y, and Poisson's ratio for loading in the y direction, ν_{yx} becomes less negative. This has no effect on properties related to loading in the x direction [38].
- Reducing diagonal rib thickness decreases the stiffnesses E_x and E_y, but increases NPRs ν_{yx} and ν_{xy} [38].
- Shear modulus was found to increase with the re-entrant angle θ, and decrease as cell rib length ratio h/l increases [37].

As can be seen from these relationships improving one property will often influence other properties. While each auxetic unit cell will have different modifiable geometric characteristics, it is generally important to keep the relative density low enough so that the auxetic unit cell deformation motion is not restricted. If ribs in a re-entrant cell are too thick for example the cell may no longer behave in an auxetic manner.

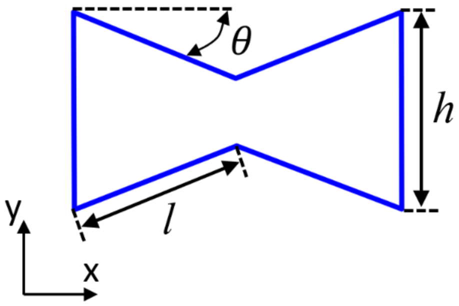


Figure 7. 2D re-entrant honeycomb unit cell.

3.1. Existing unit cells

The following tables provide a list of unit cells that commonly appear in the literature; more detailed design information and experimental data can usually be found in the relevant design papers. It should be noted that information in the following tables has been taken from a variety of papers and as such some unit cells may have more information available than others.

3.1.1. Re-entrant

Re-entrant unit cells are based on connected diagonal ribs which deform to produce an auxetic effect when placed under an applied load [2]. The point where the ribs join acts as a hinging mechanism. It can be seen from section 3 that re-entrant cells are a commonly used type. This is likely due to them being shown to have high stability, load capacity, and ductility in dynamic load cases [11,29,39,40]. Table 1 lists several re-entrant unit cells with design notes from the literature.

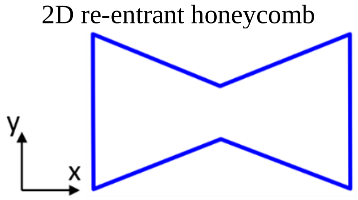
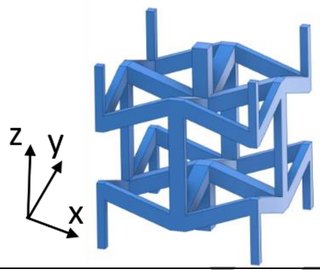
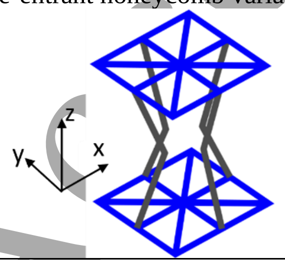
3.1.2. Chiral

Chiral unit cells are typically formed of ligaments attached tangentially to rigid nodes [2,41]. When the rigid nodes rotate, the attached ligaments either wind or unwind, which leads to auxetic behaviour. Most chiral unit cells can be classified into chiral, anti-chiral and meta-chiral configurations. Table 2 lists several chiral unit cells with design notes from the literature.

3.1.3. Rotating rigid shape

Rotating rigid shape cells are formed from rigid polygons which are joined at the corners by material that acts as a hinge. As these structures are loaded the rigid polygons rotate, which causes the auxetic effect [2]. Table 3 lists several rotating rigid shape unit cells unit cells with design notes from the literature.

Table 1. Re-entrant unit cells with design notes from the literature.

Unit cell	Design notes	Ref.
2D re-entrant honeycomb 	Poisson's ratio: Negative in both axes. Isotropy: Highly anisotropic, the degree of which depends on the values of the geometric parameters in the image. Reduction in vertical rib thickness reduces stiffness in y direction and the NPR when loaded in the y direction. Equations linking the unit cell parameters to its mechanical behaviour have been proposed.	[37,42–44]
3D re-entrant honeycomb variant 1 	Isotropy: Highly anisotropic. The structure shows NPR in all three principal directions. Due to symmetry, the mechanical properties along the *x* and *y* axes are the same. As design in 3D re-entrant honeycomb is based on the 2D re-entrant honeycomb similar parameters can be modified to produce similar effects.	[45–47]
3D re-entrant honeycomb variant 2 	Poisson's ratio: Poisson's ratio of −1.8 estimated through computer aided design. Isotropy: Highly anisotropic. The normalized Young's modulus (Young modulus of the lattice structure/Young modulus of the bulk material) reached values is 0.0002.	[48,49]

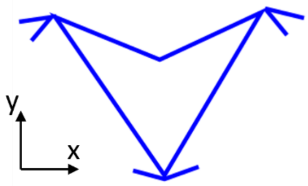
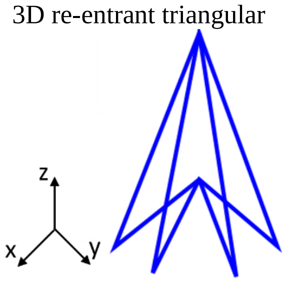
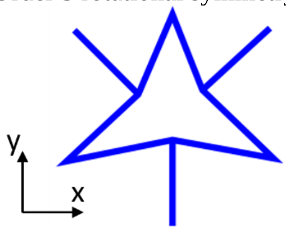
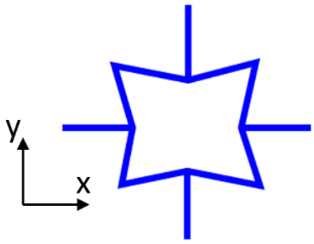
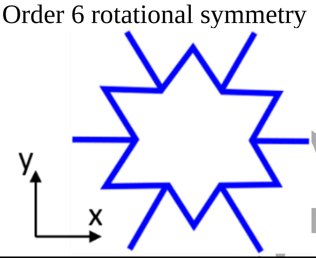
2D re-entrant triangular 	Poisson's ratio: Negative when loaded in y direction. Poisson's ratio of -0.92 ± 0.13 was achieved experimentally. Isotropy: Highly anisotropic. When placed in vertical compression the triangles collapse and contract horizontally. NPR depends on length of ribs and angle between them.	[50]
3D re-entrant triangular 	The mechanical properties and energy dissipation of the system made of this unit cell varies significantly depending on the plane considered as well as the loading direction. The system shows isotropic behaviour in some planes. Systems composed of this unit cell have been prototyped in a pin-jointed manner.	[51–53]
2D re-entrant stars: Order 3 rotational symmetry  Order 4 rotational symmetry  Order 6 rotational symmetry 	Auxetic behaviour arises from opening of stars and the magnitudes of the Poisson's ratios highly depend on stiffness of the hinges which connect the rod elements. The systems made from stars of rotational symmetry of order 6 and 4 have a greater potential for exhibiting auxetic behaviour than the systems with rotational symmetry of order 3.	[54]

Table 2. Chiral unit cells with design notes from the literature.

Unit cell	Design notes	Ref.

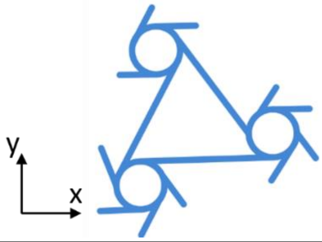
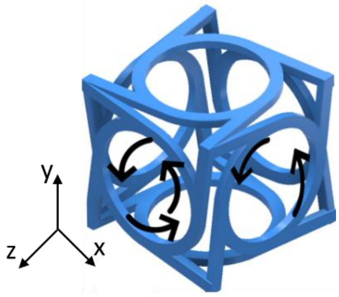
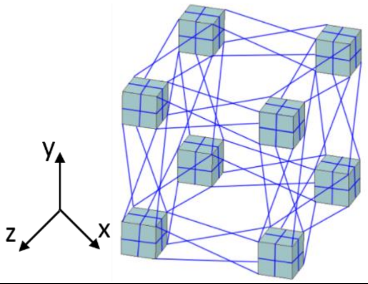
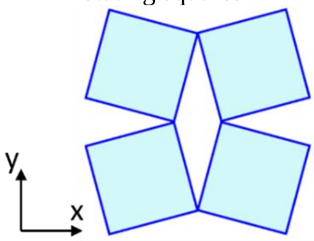
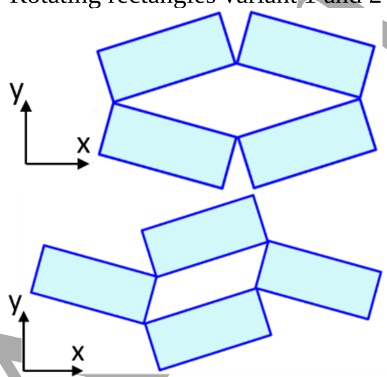
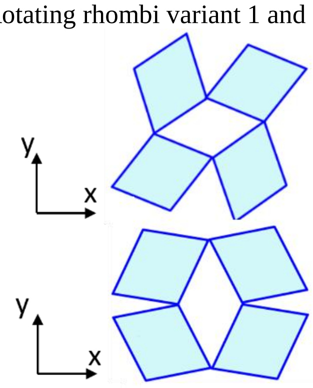
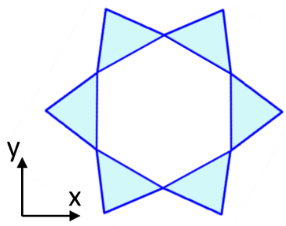
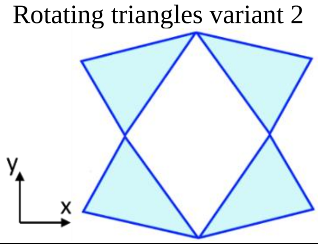
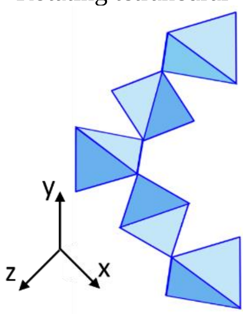
Chiral honeycomb 	Poisson's ratio: -1, which is independent of strain for small deformations. It has been suggested that keeping relative density of this unit cell below 0.29 will ensure the deformation mechanism to be primarily auxetic. Equations linking the unit cell parameters to its mechanical behaviour have been proposed.	[55]
Twisting 3D chiral 	The structure twists upon compression of the unit cell and the effect is maintained on the macro scale when tessellated into a lattice. By switching between left-handed and right-handed chiral structures, the twisting direction can be changed. More enclosed unit cells in the lattice will stiffen it.	[56]
3D chiral 	Poisson's ratio is geometry dependant. Increasing the number of cells in a lattice decreases Poisson's ratio from positive to negative. The Lattice is prone to size effects. Isotropy can be obtained by adjusting the of aspect ratio of the unit cell.	[57]

Table 3. Rotating rigid shape unit cells with design notes from the literature.

Unit cell	Design notes	Ref.
Rotating squares 	Poisson's ratio: -1. The off-axis mechanical properties obtained from the standard transformation equations show that this system composed of rotating squares is isotropic, which means that the Poisson's ratio has a constant value of -1 irrespective of the direction of loading.	[58]
Rotating rectangles variant 1 and 2 	Rotating rigid rectangles of the same size show two different structures, variants 1 and 2, depending on the connectivity, which have very different mechanical properties. Poisson's ratio depends on aspect ratio of rectangles, angle between them, and direction of loading.	[59]

Rotating rhombi variant 1 and 2 	Rotating rigid rectangles of the same size show two different structures, variants 1 and 2, depending on the connectivity, which have very different mechanical properties.	[60]
Rotating triangles variant 1 	Poisson's ratio: −1. Isotropy: Isotropic when the triangles are equilateral and perfectly rigid, the Poisson's ratio will always assume a constant value of −1 irrespective of the size of the triangles, the angles between the triangles and the direction of loading.	[61]
Rotating triangles variant 2 	This variant is composed of triangle with three different side lengths and different angles (transition angle) between them. Systems composed of equilateral, isosceles and scalene show non-auxetic behaviour, i.e., Poisson's ratio is positive for all values of transition angles. The very high positive Poisson's ratio results in exhibiting negative linear compressibility (NLC) i.e., expand rather than shrink in at least one direction under compressive hydrostatic pressure, along particular directions.	[62]
Rotating tetrahedral 	3D version of 2D rotating polygons. Poisson's ratio: Negative in all three principal directions, being isotropic in the transverse plane but anisotropic elsewhere. The magnitude of the Poisson's ratio is dependent on the tilt angle of the tetrahedra (i.e., is strain-dependent).	[63]

3.2. Unit cell selection

Choosing which auxetic cell structure to use in an application depends on wide variety of factors and considerations. Some good questions to ask are:

What properties of auxetic structures do you hope to use in this application?

To begin with, the essential requirements of an application will need to be laid out. Which core requirements are being filled by auxetic properties and behaviour? What other requirements exist?

For example, in some applications auxetic structures are used for their ability to expand under tension wherein the magnitude of the NPR is the property that must be focused on. However, a certain minimal level of stiffness may be required. The design challenge then is to find a cell that maximises NPR while staying above a required stiffness.

The properties and limitations of each unit cell will show how suitable they are. It is worth noting how structural properties can be changed by modifying the unit cell geometry, as this will ultimately affect how the cell can be optimised for an application.

How much strain will the structure be under?

Some unit cells rapidly lose their auxetic properties if under more than a small strain. Some unit cells can only deform so far due to their geometries. Some unit cells will also experience more maximum localised stress compared to others at the same strain.

Will the strain be tensile, compressive, or both?

Due to the nature of their geometry some unit cells only exhibit auxetic behaviour for a single type of strain or are more limited in one type of strain. It is important to consider which types of strain an application requires.

How many dimensions matter?

What directions is the auxetic cell expected to be loaded in? Will loading only ever come from one dimension, two dimensions, or all three?

An important trait of an auxetic unit cell is whether it is a 2D or a 3D unit cell. 2D unit cells can be described by 2D geometry, when manufactured this geometry will be given a strut thickness/extrusion length and possibly a curvature to conform to. 3D unit cells on the other hand must be described by 3D geometry. A 3D version of the 2D unit cell from Figure 7 is shown in Figure 8; this 3D re-entrant structure was first proposed by Evans et al. [45]. 2D unit cells can only ever exhibit auxetic behaviour in two different dimensions, whereas 3D unit cells can exhibit auxetic behaviour in all three dimensions. Therefore, applications that require an auxetic response in all three dimensions must use a 3D unit cell, an example of this is an impact resistance application where the impact can come from an unknown direction.

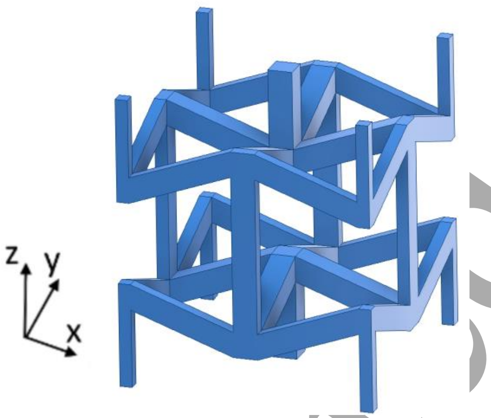


Figure 8. 3D re-entrant honeycomb unit cell.

If the structure is loaded in more than one dimension, or if the expansion response in more than one dimension matters then the level of isotropy/anisotropy may matter. If loading ever occurs in two dimensions, a 2D unit cell can be used. If loading may occur in all three dimensions, then a 3D unit cell is required.

What space is free around the unit cell?

When under tensile loading an auxetic structure will expand transverse to the loading direction. The surrounding free space in an application to expand into may limit the choice of unit cell.

In cellular auxetic structures, the motion of the unit cell is what leads to auxetic behaviour. Anything that blocks or affects this motion will change the auxetic effect. Intrusions and blockages in an auxetic lattice will restrict the unit cell motion and so limit the auxetic behaviour. Similarly attaching fixed structures to multiple sides of a unit cell may restrict unit cell motion. A unit cell with a motion that is not restricted by the application environment should be selected.

General guidelines

At present there is not a completely structured method for choosing which unit cell is best for a given application.

A higher NPR will mean a more auxetic response which tends to result in more of the beneficial auxetic properties [32]. It would be easy to assume that this means the unit cell with the highest potential NPR should be picked. This cell may also have a low stiffness, an NPR that rapidly decays as strain increases, be highly anisotropic, or have large amounts of localised stress in the unit cell when strained. For this reason, unit cells with a higher potential NPR should be picked providing they do not negatively impact the application's core requirements.

In general, it is good to see if the known unit cells have been used in any applications similar to the one being designed for. Some cells such as the re-entrant honeycomb have proven their versatility and use in several different applications as seen in section 3. It can be difficult to determine which unit cell would be best for an application before going through a cell optimisation process, so it may be useful to take a selection of cells through the optimisation step described in section 8.4 then down select after. Optimizing a unit cell for one property will often influence other properties.

4. Applications

For auxetic materials to be beneficial in an application, the properties of the auxetics must match the core requirements of the application in some way. The following examples show how auxetics have been selected for, then integrated with an end-use application, and why.

4.1. Sandwich Structures

Sandwich structures are often required to minimise weight while maximising structural properties [32]. Auxetic structures boast improved shear, indentation, fracture, impact resistance and energy absorption. These properties combined with a low-density cellular structure make auxetics very suitable for sandwich structures.

The ability to tailor the unit cell to optimise specific properties could allow each sandwich structure - or region of a sandwich structure - to be designed for its end-use application. A sandwich structure's panels also help with distributing loads over the cellular structure, avoiding edge cases where the load is taken by one strut.

Thanks to the versatility of sandwich structures, it is easy to imagine auxetics being applied in a wide variety of industries to create lightweight but strong structures. Yang et al. [32] designed a sandwich panel that has been designed for a bending application being tested for bending stiffness. This panel was additively manufactured using electron beam powder bed fusion (EB-PBF) with Ti-6Al-4V powder. It was shown that the auxetic structures exhibited increasing bending compliance and energy absorption as the NPR of the designed cells increased.

Bodaghi et al. [32] have experimented with making reversible energy absorbing sandwich structures that feature alternating layers of hard and soft material, as shown in Figure 9. It was found that dual material sandwich structures could create a range of non-linear stiffness and energy dissipation capacities. The softer material layers provide elastic absorption of low energy impacts, and work to spread the load on the rigid layers in the case of high energy impacts. The reversible sandwich structure from Figure 9 was subjected to a load-displacement experiment. The structure at the start and end of being loaded can be seen in Figure 10. At the end of the experiment any plastic deformation was undone by thermal shape recovery.

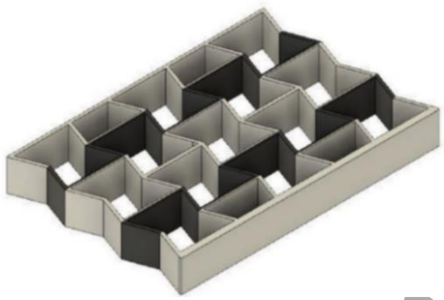


Figure 9. Dual material auxetic structure. Made of alternating black soft material (FlexPro) and white hard material (SMP) [31].

Figure 11 shows the force-displacement behaviour of the structure over the course of the experiment and the energy that is dissipated or absorbed. The force-displacement results show a relatively flat force response up until 13.5 mm which is thought to be due to the soft elements with lower stiffness deforming more. From 13.5 mm onwards the structure starts to harden as the force is transferred more to the hard elements and densification initiates [32]. Densification in this example refers to the auxetic behaviour causing material to flow into the collision location which causes local hardening behaviour as shown in Figure 6. The hardening of the auxetic lattice as displacement continues can be seen in Figure 11 as an increase in force that lasts until the maximum load displacement.

Work done by Bodaghi and Liao [64] has also taken a close look at shape memory effects in additively manufactured auxetic sandwich structures and how to model the behaviour of these sandwich structures using Finite Element Analysis (FEA). The shape memory effect on a loaded auxetic structure can be seen in Figure 12 which demonstrates how auxetic sandwich panels may use the shape memory effect to recover from being loaded past the elastic threshold.

Auxetic sandwich panels have also been examined for use in impact and close-range blast response. Figure 2 (e) shows a panel that has gone through a drop weight impact test. The panel was made from folded aluminium sheets bonded with epoxy resin. Following the impact test this panel design was then subjected to a blast test. During testing, the auxetic core was found to absorb 19.1% more energy than the equivalent conventional core [16]. Figure 13 shows the energy absorption curve of the drop weight impact test for both auxetic and conventional cores, auxetic cores are shown to absorb more energy at a faster rate during impact.

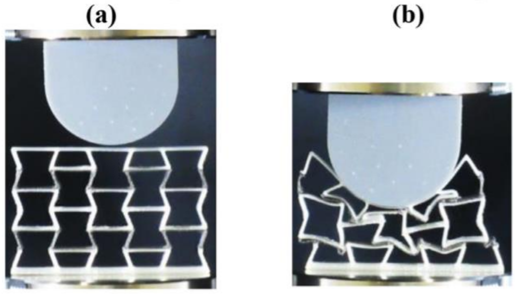


Figure 10. Start and end of loading of dual material auxetic structure [31].

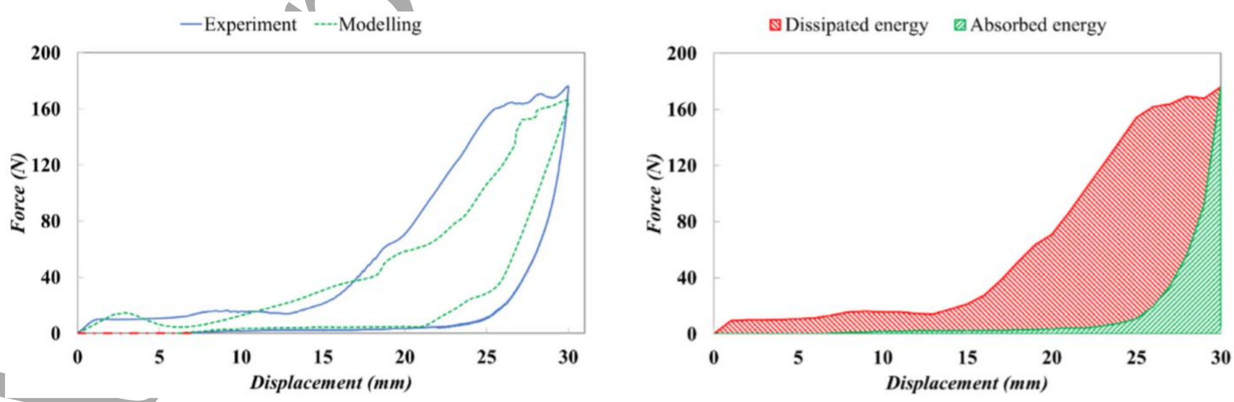


Figure 11. Dual material sandwich experimental data. Left: Force-displacement data for loading-unloading. Red dash-dotted line represents thermal shape recovery. Right: Dissipated and absorbed energies [31].

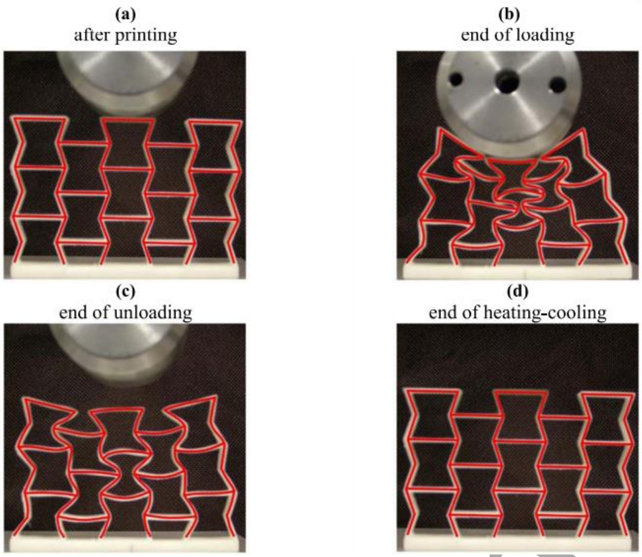


Figure 12. Loading, unloading and recovery through heating-cooling using shape memory effect on an auxetic structure [64].

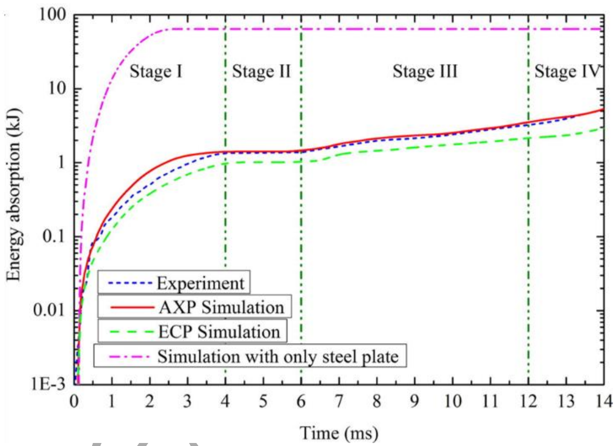


Figure 13. Energy time history in drop weight impact test. Simulated auxetic honeycomb panel (AXP) and equivalent conventional honeycomb panel (ECP) results shown. Experiment result represents experimental results of AXP [16].

4.1.1. Graded sandwich structures

In the automotive industry a crash box is widely used as a disposable part in the front bumper system to absorb energy. Graded lattices are lattices where the geometric properties of the unit cell vary in different regions of the lattice. Hou et al. [30] examined the use of auxetic panels in an automotive application. A graded auxetic cellular structure was modelled for use in this crash box, the height of the unit cell was reduced as the distance to the impact area decreased. This graded auxetic structure was attached to either end of a front bumper in a crash test loading case simulation. The final optimised structure had a lower reaction force and better energy absorption ability compared with a uniform cell design, showing the benefits of adding a grading to existing auxetic structures. Standard collision tests carried out were passed, showing the structure performs effectively in this application.

4.2. Implants

Metamaterials designed for use in the medical field are an emerging concept. Auxetic materials have found a niche in the medical field due to their unique deformation mechanism. A study from Kolken et al. [13] follows the design and fabrication of a hip stem implant with a combined auxetic and conventional structure. The created implant can be seen in Figure 2(a).

As a patient walks, the hip implant is repeatedly loaded under bending; this creates tensile loading on outside of the hip and compression on the inside of the hip. This has an important effect on the implant-bone interface. If conventional material is used then the side under tension will shrink and retract from the bone, while the compressed side will press against the bone. Retracting from the bone is linked to faster interference failure. Retraction also causes wear particles to enter the implant-bone interface, which causes a foreign body response that leads to bone loss.

It was theorised that using auxetic material on the side of the implant under tension and conventional material on the side under compression would lead to both sides expanding during gait. This was expected to improve the implant-bone interface and therefore increase implant longevity. A variety of implant designs were manufactured with electron beam powder bed fusion (EB-PBF) of Ti-6Al-4V. Tests performed as part of the design process verified that both sides of the implant were expanding when under load, as expected.

4.3. Stents

Stents are tubes that may be inserted into blocked passageways in the body in order to keep them open. Stents may be inserted into blood vessels, the oesophagus, and many other passageways. After insertion into a patient, a stent is normally inflated by a balloon catheter and is plastically deformed, fixing into place in the passageway. The catheter can then be removed, leaving the passageway open [14].

Figure 2(b) shows an auxetic stent designed for use in the oesophagus of a patient with oesophageal cancer [14]. As the stent is inflated radially, its auxetic nature also causes a longitudinal expansion. The longitudinal expansion means the stent can be more compact on initial insertion but cover more surface area on inflation. It is also expected that the anisotropic mechanical behaviour of the stent will conform well to the anisotropic mechanical response of the oesophageal wall. The stent in this study was made by casting polyurethane onto a metal reverse mould. The metal mould was additively manufactured by EB-PBF of Ti-6Al-4V.

4.4. Smart filters

Variable porosity of auxetic structures has led to interest in their use for smart filter applications. As the structure is put under strain the auxetic behaviour causes it to expand in both directions; at the unit cell scale this causes an increase in porosity. By varying the porosity different sized particles can be filtered, or different flow rates can be achieved. Figure 5 illustrates this principle: (a) shows how different max sizes of particles are filtered out, and (b) shows multiple smaller particles fit into a larger pore size which modifies flow rate.

There are multiple works that have investigated smart filter applications [10,24]. Unit cell selection is very important for this application. The cell chosen must have a pore shape which can reliably deform under strain to restrict the particles being filtered. One additional benefit that was noted from the auxetic filters is the potential for filter defouling. As filters are used, they may become clogged up with particles. To loosen the particles, an auxetic filter can have its pore size increased, and the filter can then be easily flushed. An experimental example of auxetic filter defouling was examined in the works of Alderson et al. [10], as shown in Figure 14.

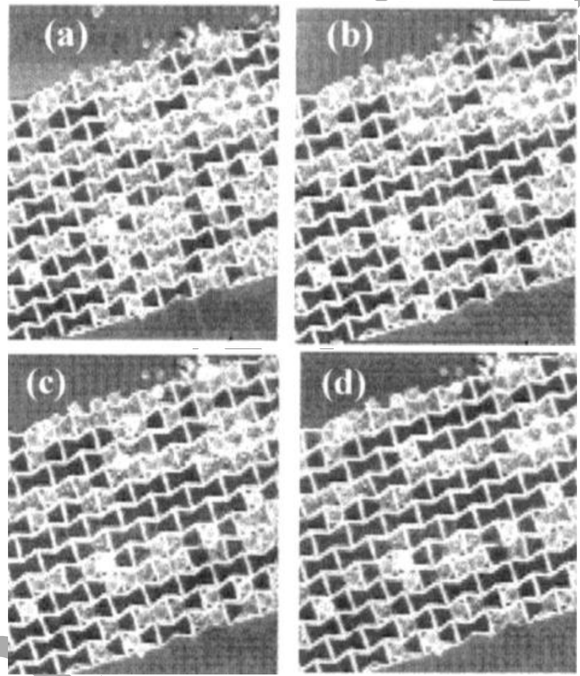


Figure 14. Auxetic re-entrant filter membrane defouling glass chromatography beads. Non-deformed membrane with 60% bead coverage is seen in (a), (b) – (d) show increasing strains with (d) having 1% strain in the horizontal direction and 30% coverage [10].

4.5. Vibration damping

Many industries require some form of vibration damping structures. It has been theorised that auxetic structures can have beneficial acoustic properties such as acoustic isolation, damping and filtering [65–67]. Figure 2(i) shows a vibration isolation base that was designed and tested for vibration frequency response.

It was found that, when compared with a conventional base, the auxetic base reduces propagation of vibrations more efficiently and has a lighter weight. As the behaviour of the cellular structure is scale-independent, this can be re-scaled for a wide range of vibration isolation applications.

4.6. Morphing structures

The ability for auxetic structures to change shape in configurable ways when under strain lends itself to the creation of morphing structures. Figure 2(g) shows an aerofoil with an auxetic truss-core which is designed to exploit elastic deformations of the aerofoil shape in a controlled manner [18]. This would allow for tailorable aeroelastic properties that could lead to reductions in complexity and weight of current wing designs. The high in-plane NPR of roughly -1 is expected to provide a high shear modulus which allows the auxetic core to support the loading requirements of the wing. Numerical and experimental results demonstrate the compliance due to the auxetic core. The results also confirm that the aerofoils can withstand large deflections while not exceeding yield strain limits.

4.7. Electronics

Ferguson et al. [15] examined the potential for using an auxetic structure in a strain energy harvesting application to increase the power output of the energy harvester. The strain energy harvester seen in Figure 2(d) consists of a piezoelectric element bonded to an auxetic substrate. When the auxetic substrate is placed under strain, it applies auxetic behaviour to the piezoelectric element and stretches it in both directions at once. The lower stiffness of the auxetic region of the substrate also concentrates the stress on the region covered by the piezoelectric elements. Both properties serve to increase the power output of the energy harvester. Experimental results show that the peak power produced by the auxetic harvesters is 14.4 times that of the plain energy harvesters.

Capacitive strain sensors can be used to convert mechanical strain signals into electrical signals. Further to strain energy harvesting purposes, auxetic structures also have use in sensing applications [17]. Figure 2(f) shows how the auxetic mechanism might affect the behaviour of a strain sensing elastomer. It is reported that this could improve the sensitivity of capacitive type strain sensors.

4.8. Sports apparel

Auxetic structures have been examined in sport applications for the purpose of improving comfort, protection and performance [23]. It has been suggested that the synclastic curvature of auxetics would make them more form-fitting. This combined with superior energy absorption and indentation resistance properties is expected to make them particularly well suited to protective sport equipment. Foster et al. [68] examined the difference between using auxetic and conventional foams as a conformable layer in a sports helmet. This was done to improve helmet performance in linear impact scenarios. The auxetic foam reduced peak linear accelerations and impact severity.

Two different shoes from leading brands have incorporated auxetic structures into their design in different ways [3]. A shoe from Under Armour has auxetic skin which can benefit from the increased conformability that the synclastic curvature property provides. A shoe from Adidas has an auxetic sole that can benefit from improved energy absorption and impact resistance.

5. Manufacturing methods and material selection

Manufacturing of auxetic materials was first reported by Lakes [9], who developed a method of converting conventional open-cell foams to auxetic foams. This was done through compression, heating and cooling. A more recent review of this process was done by Critchley et al. [5]. One limitation with auxetic foams is that although the manufacturing parameters can be changed, it is not possible to completely customize the design of the unit cell. Since the initial work from Lakes [9], alternative auxetic unit cells have been investigated for use in applications. These have been manufactured in several different ways that will be described in the following sections.

5.1. Conventional manufacture

Conventional machining methods are suitable for a wide range of 2D auxetic cell geometries, but struggle with the fabrication of 3D unit cells. An example of a 3D auxetic is the stent design by Ali et al. [14]. While prototyping an oesophageal stent, Ali et al. [14] tried out a variety of manufacturing methods. Polyurethane was selected as the material due to its biocompatibility and non-toxicological behaviour. This polymer's properties can also be tailored. A variety of different manufacturing methods were used in the testing and development of the final produced stent. For tensile testing of the unit cell, a flat film was laser cut. Next a collapsible mould was used to cast the resin into a prototype stent as seen in Figure 15.

Figure 15. Collapsible mould used to cast resin into a prototype auxetic oesophageal stent [14].

Lastly, a silicone mould was made using vacuum casting of a master model and used to cast the final stent. It should be noted that although the stent has a 3D shape, the unit cell is still 2D. It is effectively a 2D sheet that has been rolled up.

In the works of Qi et al. [16] Sandwich panel specimens were created to test for impact and blast resistance. Specimens were made from AA6061 aluminium alloy, they consisted of two face-sheets with a re-entrant honeycomb core. To make the specimens, aluminium sheets were manually folded and then bonded using epoxy resin.

5.2. *Additive manufacture*

With additive manufacture, new levels of design flexibility, rapid prototyping, less wastage and appreciable precision and accuracy can be reached [69]. This allows for 2D and 3D unit cells to be manufactured with relative ease. It also allows for additional design freedom over an auxetic lattice, such as the potential for multi-material printing, or functionally graded lattices. Depending on process, material, overhangs and part orientation, some form of support may need to be used. In most cases, the 2D unit cell lattice is flat and does not require support, such as in Figure 16. But sometimes the 2D unit cell may be designed to conform to a curved surface.

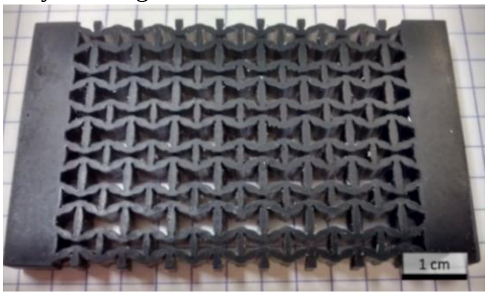


Figure 16. 2D lattice manufactured using stereolithography and a rubber-like material GM08b [70].

Some additive manufacturing methods are self-supporting. Some such as metal L-PBF are highly dependent on supports [71] and will need support structures for any significant overhangs in the part. Some processes use soluble supports that can be dissolved in fluid. Non-soluble supports may be easy or extremely challenging to remove. Any process that requires support structures inside a lattice structure will be restrictive due to accessibility for support removal.

Another important consideration is the resolution and accuracy of the manufacturing process. To achieve predictable behaviour in a lattice, a fine resolution must be used relative to the scale of the unit cell geometry.

5.3. *Material selection*

Manufacturing processes may have limitations on which material they can work with. Therefore, material selection should be considered while choosing a manufacturing method. For example, the materials available for additive manufacturing methods depend largely on the machine and process being used. The auxetic behaviour of cellular structures depends on strain deformation behaviour within a unit cell. Quite often specific parts of the unit cell may be undergoing higher localised stress than the structure as a whole due to stress concentrations. As a result, it is very important to consider the strain limits of any material selected. It is worth noting that each unit cell has a theoretical set of strain limits it can reach based on its geometry, but in reality, the cell may fail sooner based on the material limits.

The maximum strain needed for an application should be looked at in comparison to the maximum stress this causes in a unit cell, and a material which can match this stress level should be selected. In reversible applications, the elastic limit must be above the maximum stress; this means more flexible material is needed for an application to be reversible, such as in springs. In irreversible applications, such as crash helmets, the ultimate tensile strength should be used instead. Irreversible applications allow the benefits of more rigid materials that plastically deform under expected loads to be used.

Other material properties may be relevant depending on the specifics of the application, such as operational temperature, toxicity, machinability, etc.

So far, the focus of auxetic research has been mostly on polymers. This might be due to the ease of 3D printing with polymers [2]. Some polymers commonly used with 3D printing are polylactic acid (PLA) or polyether ether ketone (PEEK) for material extrusion methods. Nylon and PEEK are commonly used in powder bed fusion methods. Polymers are generally a good fit for auxetic structures. They typically have a low density; this helps in applications where weight is an important criterion. They also tend to have high elasticity, which allows the material to endure the deformation required for auxetic behaviour and makes polymers a good fit for reversible applications.

When high structural strength requirements need to be met, metallic materials may be more suitable for auxetic structures [2]. Metallics generally have higher stiffness and strength than polymers. Yang et al. [72] studied the energy absorption capabilities of auxetic structures manufactured with EB-PBF. The structures tested were made of Ti6Al4V and pure copper as can be seen in Figure 17. It was found that the ductility of the pure copper structure allowed for a higher energy absorption capacity compared to Ti6Al4V. The copper structure showed a smooth patterned stress-strain curve linked to a controlled buckling of the sample during compression.

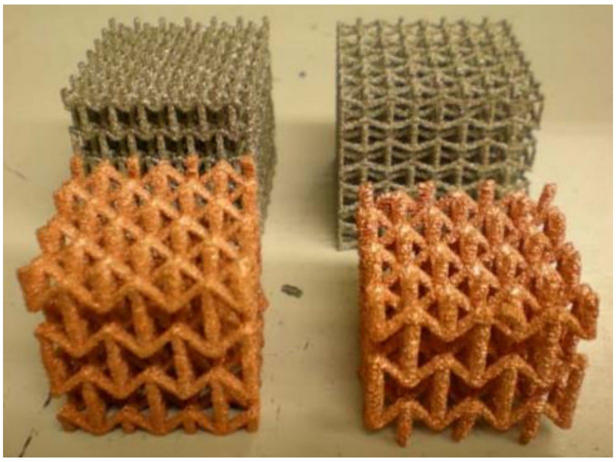


Figure 17. EBM Manufactured Ti6Al4V and pure copper auxetic structures [72].

6. Characterisation tests

When ensuring an auxetic structure meets the requirements of an application, or validating an FEA model of a unit cell, experimental tests are necessary. The followings are a set of tests that may be used to characterise the performance of auxetic structures and components that integrate them.

It should be noted that any of these tests may be used to validate an FEA model of a unit cell. This allows for using simple experimental test cases to create complex simulated test cases.

6.1. Compression/tension tests

Some of the most basic forms of characterisation tests are uniaxial compression/tension tests. These tests are useful for applications where an auxetic structure will be simply loaded in a single axis. Poisson's ratio describes how a material acts while under tension/compression, meaning they are also a good way to test the Poisson's ratio of an auxetic structure.

An example of uniaxial tensile tests was performed while making an auxetic stent [14], the test was done using a tensile tester and load cell as seen in Figure 18. The load applied was increased manually and the longitudinal/transverse extensions of the specimen measured at every load increment. In this way the Poisson's ratio could be measured as well as the stress-strain response. Uniaxial compression tests were performed while measuring the energy absorption ability of two metallic auxetic lattices [72]. Test samples were placed between two platens of a universal testing machine and an extensometer attached to the platens, as shown in Figure 19. This allowed for the stress-strain response of the samples to be measured during compression. Auxetic structures are not usually isotropic and have different mechanical responses when loaded in each axis. If an auxetic structure is expected to be loaded in multiple directions as part of an application, then uniaxial tests should be carried out in different directions to characterise the structure.

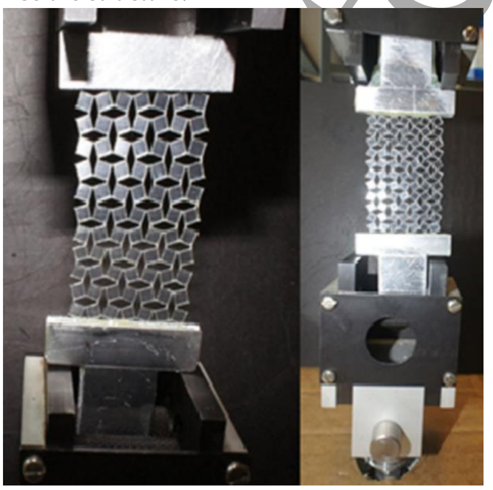


Figure 18. Uniaxial tensile test on an auxetic sample [14].

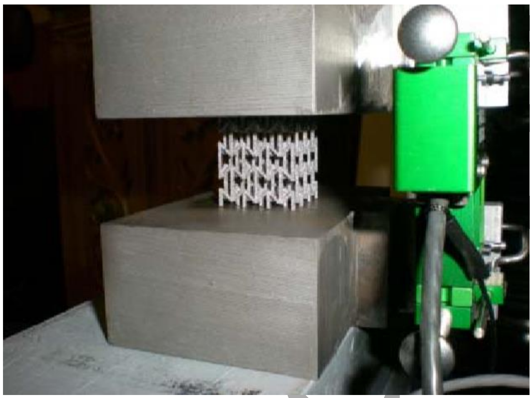


Figure 19. Uniaxial compression test on an auxetic sample [72].

6.2. Bending tests

As stated previously, auxetic structures are known for good mechanical resistance properties, and as such bending performance may be of interest in an application.

Three point bending tests may be used to characterise bending stiffness of auxetic structures [19,32]. An example of this test can be seen in Figure 2(h). Alternative methods may use an off-axis compression force [13].

6.3. Impact resistance tests

When testing for impact or blast resistance applications, it is necessary to use test equipment that can create an impulse load on a specimen. An example of a high energy impact test setup using a drop weight can be seen in Figure 20. A similar but low energy impact test setup using a drop weight was described in the works of Yang et al. [32]; this setup was designed to evaluate impact protection from small objects and debris. For drop weight tests, the cells should be covered by a sheet of material to spread the load over several cells. For testing for a blast resistance application, then drop weight tests may be useful initially, but a field blast test setup should be used if possible [16]. Figure 21 shows an example of a blast test set-up.

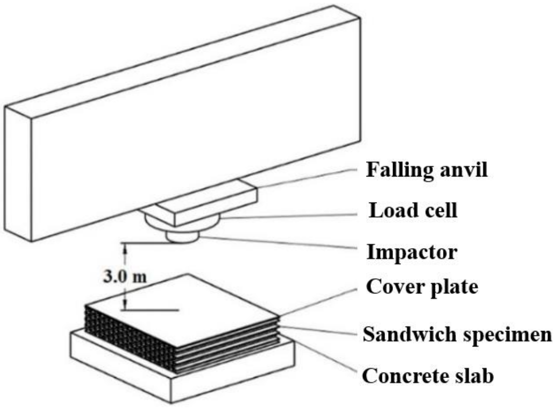


Figure 20. Impact test setup using drop weight [16].

Figure 21. Field blast test setup of auxetic panel [16].

6.4. Cell deformation tests

Cell deformation tests allow for the auxetic deformation mechanism of a unit cell to be examined for a particular test case. These tests can give insights into how the unit cell deformation gives rise to auxetic behaviour and highlight strain concentrations in the cell. These will be performed alongside some form of loading test, so that the deformation for that load can be examined. One way of testing for cell deformation is by finding the displacement field using Digital Image Correlation (DIC). In one example DIC was done using CorrelManuV 2D software to calculate displacement of 2D unit cells under tension [70], the results can be seen in Figure 22. The figure shows that the top of the unit cell has deformed upwards, and the bottom has deformed downwards, while the rest of the cell has stayed roughly the same. A white speckle pattern was airbrushed onto the sample to improve measurement precision.

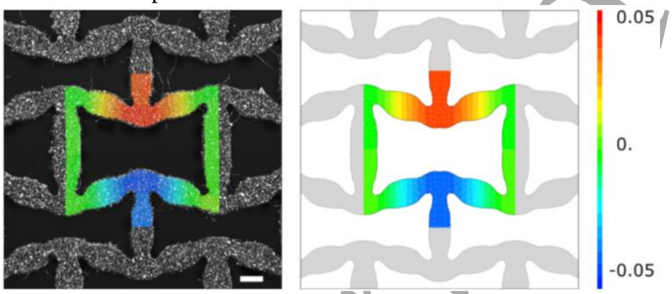


Figure 22. Vertical displacement field of unit cell under tension, produced by DIC measurements. Scale bar is 1mm [70].

7. Design workflow

When reviewing multiple research papers involving an end-use application for auxetic structures, a basic design workflow emerges. A chart outlining this design workflow can be seen in Figure 23. A summary of each step and the process required is outlined in the following sections.

7.1. Step 1 - Requirements Capture

When designing for an application, the requirements must first be captured and collected. Proposed requirements for an application should have priorities assigned to them so that vital requirements can be separated from 'nice to haves.' This information will feed into and dictate how the auxetic structure is designed and optimized.

7.2. Step 2 - Check requirements against auxetic benefits/limitations

Once the requirements have been captured the potential benefits of auxetic structures must be compared with requirements to check if auxetics are suitable for the application. It may be that the most important requirements are not helped by auxetic properties, meaning auxetic structures may add complexity to the design with little benefit.

It is also worth considering the limitations of auxetic cellular structures. Popular auxetic lattices take the form of open cellular structures which are porous. Auxetics also expand and shrink in unusual ways that are usually desirable but can cause issues if not accounted for in the design. For instance, an auxetic structure used as an energy absorber and placed under tension expands laterally, requiring a large clearance around itself where a conventional structure does not.

A good set of questions to ask is as follows:

- What are the desired properties of the final design and which of these rely on auxetic behaviour?
- Are these requirements realistic?
- What size of unit cell is needed?
- Can the auxetic structure be manufactured at the desired quantity and size?
- What about reliability, fatigue life and failure modes?
- Could it reliably be inspected for quality assurance purposes?

If the benefits of auxetic structures match the core requirements of an application and the limitations are not a concern, then the auxetic approach can be considered fit for the application. If the benefits meet some of the core requirements but also introduce some limitations, then time should be spent to consider whether auxetic structures are worth it. If benefits are minimal or limitations are numerous then auxetic structures may be a bad fit for the application. It may be useful to review the auxetic properties in Section 2 and the general guidelines from Section 3.2 while deciding this.

7.3. Step 3 - Unit cell selection

Section 3 provides detailed information on different types of auxetic unit cells, and factors to consider when selecting one for an application. Currently, many of these unit cells have not been fully characterized in the literature, and there is not a completely structured approach in place for selecting the one most suited to an application. But by following guidelines outlined in Section 3, it is possible to make a logical selection.

Unit cell selection also depends on other factors than whether the selected geometry can fulfil the application requirements. The most important of these other factors are the manufacturing methods and material selection.

As there is some uncertainty in which unit cells would perform best when optimized, it may be wise to take multiple unit cells into the next design stages. The number of different unit cells that can be taken through the next stages will depend on the allowed time and cost for design work.

7.3.1.Material selection

The range of materials which is usable will depend on the manufacturing method, which in turn depends on unit cell selection. Due to this, material selection can take place only once the unit cells have been decided on. For example, if AM is to be used then the materials available will depend on the AM process selected. A material suitable for the process that is closest to the desired material properties must be chosen.

If material optimisation is to take place later, then a selection of likely materials should be chosen and taken into the later stages, rather than choosing a single material. When using FEA for unit cell optimisation, the amount of materials considered can impact design time/cost and therefore should be taken into account. More detailed considerations for the material selection process can be found in Section 5.3.

7.3.2.Manufacturing method

The possible manufacturing methods should be considered alongside material selection as the manufacturing method will restrict the choice of usable materials.

Manufacturing methods required to fabricate an auxetic structure depend on the geometry of the structure. Some structures are complex enough that they need to be additively manufactured whereas others can be manufactured in more traditional ways. More detail on this topic can be found in Section 5. The manufacturing methods available for an application will need to be considered when choosing the unit cell. Note that the size of a component or the scale of production required may make some methods unsuitable to use, even if they are technically possible for a one-off.

If an AM method is being used, then design for additive manufacturing (DfAM) practices should be observed. One thing to note is that AM methods often result material behaving in a slightly anisotropic manner due the addition of material in layers; for this reason, build direction may affect unit cell behaviour. Once chosen, the same manufacturing method should be used across the steps for a single iteration of the design process. This is because the method used can affect the mechanical properties of the material and changing the method may invalidate the characterisation of a unit cell/validation of FEA.

7.4. Step 4 – Check if analytic behaviour of chosen unit cell is known

After the unit cell and material has been selected the literature can be checked for known analytical methods that will predict the behaviour of the unit cell.

If the unit cell behaviour is known and characterised then step 5 may be carried out next, if not step 6 must be carried out first to characterise the unit cell behaviour.

Note that analytical methods may only hold true for certain types of materials. For example, analysis created for unit cells made of a material which is linear under strain may not apply to a material which is non-linear under strain. If a new unit cell is being created, then no characterisation will be known. If a known unit cell is used but with a new type of material, or optimisation is to be performed on a unit cell that may cause it to deviate from known behaviour and then this may invalidate the known characterisation. In either case step 6 should be carried out next.

7.5. Step 5 – Lattice FEA, mechanical testing and validation

When the unit cell behaviour is known and characterised, a validation step can be carried out on a simple lattice structure. An FEA model must be tuned such that it agrees with results from the mechanical testing of a simple lattice; the same model can then be used to predict behaviour of an arbitrary lattice structure created for an application. This method depends on the unit cell geometry for the arbitrary lattice remaining a similar shape to the unit cell in the mechanically tested simple lattice, for example if a 2D re-entrant unit cell with specific parameters was tested then the model validated with those tests will only apply to a 2D re-entrant unit cell with similar parameters. This process should be performed for each unit cell that has been carried through to this design stage.

A unit cell should be modelled using finite element analysis (FEA) with the same material characteristics planned for use when manufacturing it. This will be repeated for each material being considered after the earlier material selection outlined in Section 7.3.1.

If numerical equations are known that directly link the design parameters of a unit cell and the material used to the mechanical properties of a structure, then validation can take place based on these equations rather than the results of FEA. However, usually these equations are either not known or cannot properly predict the behaviour of a structure for the desired application. In this case some form of FEA must take place. Any validation step will need to be repeated for each material considered after the material selection process. Having multiple materials may quickly add up to extra time and budget spent on this step.

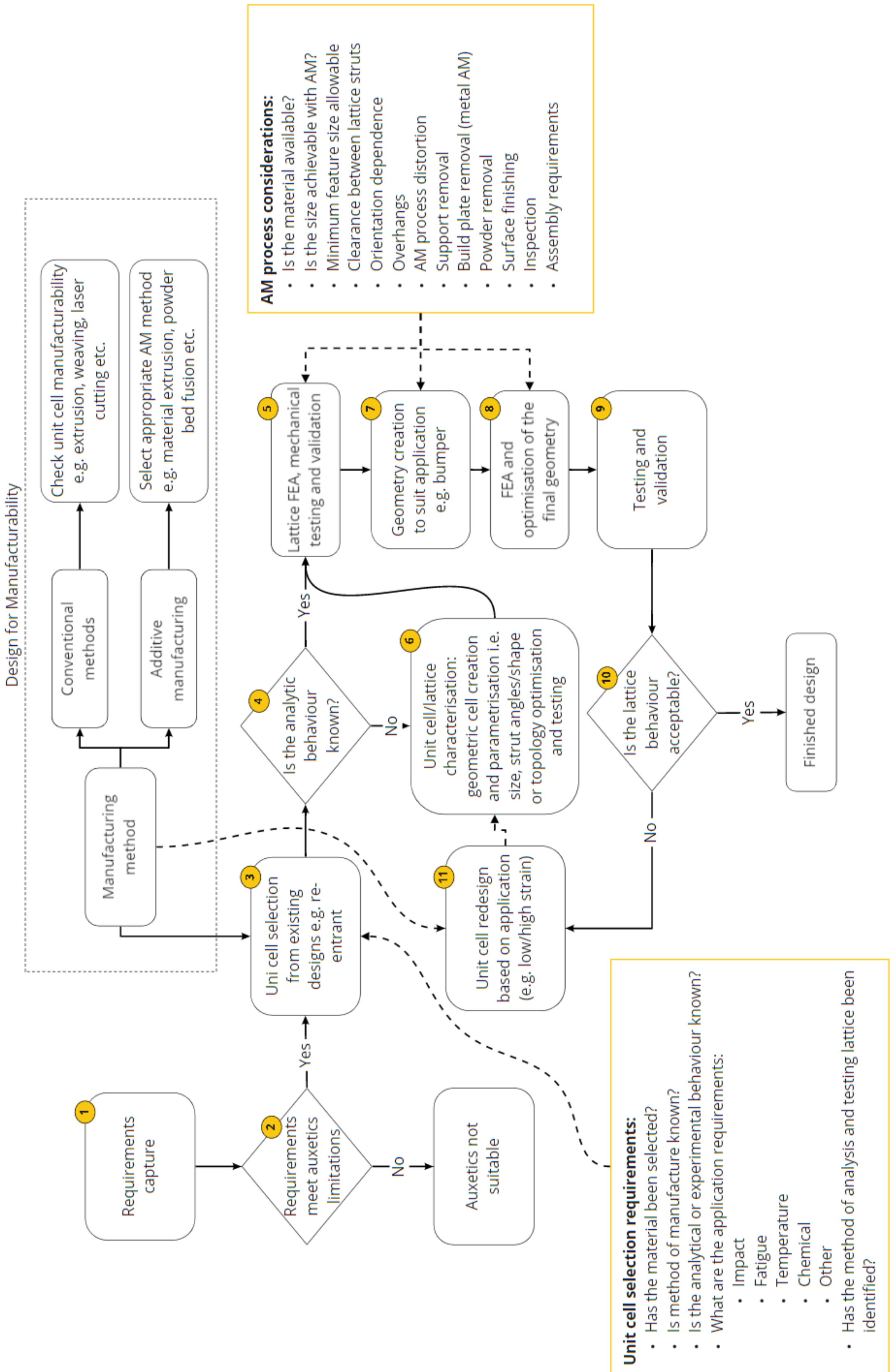


Figure 23. Auxetic design workflow

7.5.1. Finite element analysis

7.5.1.1. Build unit cell model

To start with, a model of the unit cell must be built in the FEA software. Most unit cells can have some geometric parameters modified later while maintaining the same general shape. One should choose values for these parameters that seem generally sensible and describe the expected geometric shape well. For example, the unit cell size and thickness can be set to a roughly expected range for the application, however changing strut angles in a re-entrant unit cell will cause it to behave very differently and so the angle used for validation must be close to the angle used for the final geometry. If the geometric shape of the validated unit cell varies too much from the shape of the final unit cell, then FEA results using the final unit cell may be invalid.

7.5.1.2. Test unit cells to validate FEA

This step is crucial to get realistic outputs from the FEA model. After modelling the unit cell, one should create a basic lattice and run an analysis based on an expected use case, to check if it deforms as expected.

A basic lattice must be made using the modelled unit cell from the previous step. This lattice will need to be fabricated using the chosen manufacturing method and experimentally tested. Care must be taken to ensure the lattice can be made using manufacturing methods on hand and tested in the proper machinery.

Experimental tests used to validate the lattice should match the loading of a standard use case where possible. Some examples of tests that can be performed are found in Section 6. The test performed on this lattice must match an analysis performed in the FEA software. The FEA model can then be adjusted based on the experimental results until they both agree.

Validation of the FEA model should only be performed once for each unit cell/material combination. Changing the geometric characteristics of the unit cell should not invalidate the FEA model, which will be important for the upcoming steps. What this means is that this validated model can be used for future applications providing the material/unit cell combination remains the same. Using a different material or geometry of unit cell will however invalidate the model.

7.5.1.3. Material homogenization of lattice simulation

Material homogenization is a methodology that treats the bounding volume of a lattice as a bulk material for simulation purposes rather than trying to simulate the mechanical motion of every individual strut. This makes the modelling of the lattice simpler and reduces simulation time. Homogenization of mechanical metamaterials with hierarchical patterns is normally performed by considering a representative volume element (RVE) and implementing periodic boundary conditions (PBC). The PBCs method entails the simulation of a structure as an infinite system with all pairs of opposing boundaries (two or three depending on whether the system is 2D or 3D, respectively) deforming in an identical manner [73]. There are different schemes to implement PBCs and only through choosing the right one and implementing it correctly, the simulations can realistically output the deformation behaviour of the system.

7.5.2. Known equation analysis

Equations exist that describe how the properties of a known auxetic unit cell change with variations in other factors. One example of this is the theoretical model for 2D re-entrant honeycombs, this model was developed by Masters and Evans [43] with the flexure model provided by Gibson et al. [74]. Masters and Evans used the deformation model to derive a set of elastic property equations for the unit cell and co-ordinate system shown in Figure 24.

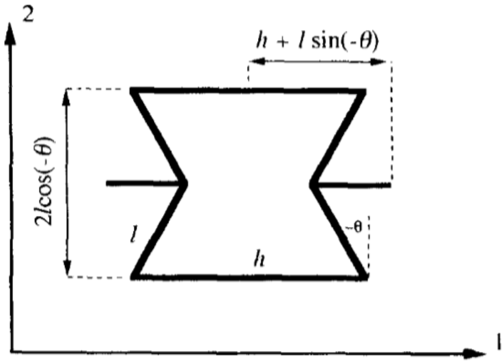


Figure 24. Cell geometry and co-ordinate system used for equations [43].

Figure 24 defines variables *h*, *l* and θ as well as the co-ordinate system. Strut thickness is *t* and depth is *b*. *E* is the Young's modulus of the cell structure, *G* is the shear modulus and ν is the Poisson's ratio. K_f is the flexure force constant and E_s is the Young's modulus of the material used to make the cell. The equations below were created for the unit cell and can be used to optimise its mechanical properties for an application by altering its geometric design [43]:

$$K_f = \frac{E_s b t^3}{l^3} \tag{2}$$

$$E_1 = \frac{K_f \left(\frac{h}{l} + \sin\theta\right)}{b \cos^3\theta} \tag{3}$$

$$E_2 = \frac{K_f \cos\theta}{b\left(\frac{h}{l} + \sin\theta\right)\sin^2\theta} \tag{4}$$

$$v_{12} = \frac{\sin\theta\left(\frac{h}{l} + \sin\theta\right)}{\cos^2\theta} \quad (5)$$

$$v_{21} = \frac{\cos^2\theta}{\sin\theta\left(\frac{h}{l} + \sin\theta\right)} \quad (6)$$

$$G_{12} = \frac{K_f\left(\frac{h}{l} + \sin\theta\right)}{b\left(\frac{h}{l}\right)^2\left(1 + 2\frac{h}{l}\right)\cos\theta} \quad (7)$$

Depending on the known equations either material optimisation or size optimisation may be performed. This could be done manually using a set of sensible values or via analytical methods that test the full value ranges. Note though that any optimisation must be performed before the validation step.

Using equations may save time and cost as opposed to validated FEA methods, but they are unlikely to produce as accurate results. It should also be noted that many unit cells in the literature have poorly defined or few known equations. Defining equations that are accurate for the full range of unit cell design possibilities is challenging.

Known equations may be derived using FEA, experimental analysis, or theoretically through fundamental mechanical equations.

7.6. Step 6 – Unit cell/lattice characterisation: creation, size, shape or topology optimisation and testing

When creating a new unit cell or using a known unit cell that does not have the analytic behaviour understood, a characterisation step must be performed. The aim of characterisation is to understand the behaviour of a unit cell such that an analytical method such as FEA can be used to predict the behaviour of a design that uses it.

Any optimisation steps that may alter the behaviour of a known unit cell must also be done in this step before characterisation. New cells may be created by methods such as topology optimisation that can produce a desired behaviour based on a specific set of design objectives and constraints. It should be noted that commercial software packages do not readily offer this functionality.

In the case of multiple unit cells being considered, this process should be performed for each unit cell that has been carried through to this design stage.

7.6.1. Optimisation Steps

7.6.1.1. FEA unit cell optimisation

Using FEA to optimise a unit cell contains the following steps:

- Build a model of the unit cell.
- Experimentally test the unit cells to validate the FEA.
- Perform size/shape/topology optimisation based on the requirements of the application.

There are two different optimisations which will commonly be performed as part of this step. Other optimisation methods may be used but these common ones will be considered for the purpose of this paper:

- Size/shape/parametric optimisation [15,20,30];
- Topology optimisation [50,70,75].

Shape optimisation involves altering the parameterized geometric characteristics of the unit cell to optimise the desirable material properties of a lattice made of that unit cell. The properties which are optimized will depend on the end-use application being designed for. Modifiable geometric characteristics of a variety of unit cells are detailed in the Section 3.

7.6.1.2. Known equation optimisation

If equations have been derived that link the geometric parameters of a unit cell to the mechanical properties it exhibits, then the effects of varying these parameters may be examined to optimise a unit cell. A more detailed example of these equations and methodology is in Section 7.5.2.

7.6.1.3. Material optimisation

Performing this optimisation step involves repeating any previous optimisation stages using each potential material selected in Section 7.3.1. This should give an idea of how each different material will affect the properties of the optimised auxetic lattice. If a variety of materials were selected and taken to this stage, then they will be compared based on which has the best performance for the application.

7.7. Step 7 – Geometry creation to suit application

Previous steps have handled the optimisation and validation of a basic auxetic lattice based on the application. But as of yet, it has not been considered how the lattice will be integrated into the designed component.

For an auxetic lattice to be effective the load should be distributed across as many unit cells as possible, with single strut loading being avoided. One good way to accomplish this is by covering any lattice ends that will be placed under load with a thin skin, such as in a typical sandwich structure. If high loads are concentrated in a small area then unit cells may have to be made smaller, to ensure load is properly distributed.

The lattice should be shaped in a way that conforms to the shape required by the application. For example, if designing an auxetic helmet the lattice would have to follow the curvature of the helmet and fit inside a cavity in the helmet. At the interface between the lattice and rest of the component some blending of material may help to relieve the stresses.

Finally, it should be considered how the lattice will interface with the rest of the part/assembly when expanding under tension/shrinking under compression. The novel deformation mechanic of auxetics may cause issues if not accounted for in the rest of the design (e.g., unexpectedly expanding into an area enclosed by surfaces or moving parts).

7.8. Step 8 – FEA and optimisation of final geometry

Modelling the final component geometry in FEA is potentially very complex and time-consuming. However, being able to predict how the component reacts to different conditions without a complex set of characterisation testing is valuable. This would help to highlight any issues in the design that may have occurred when integrating the auxetic lattice with the component. Issues that occur in the interface between the auxetic structure and rest of the component should be caught and remedied as part of this step.

The full part FEA will also give an indication of how the component will perform in the end-use application, possibly giving information that would be hard to get from simple characterisation testing. If the analysis predicts the component will not match the specification, then previous design steps can be iterated on with this data in mind. This could potentially save on manufacturing and experimental testing steps needed to reach a finished design. It should be noted though that the lattice structures often do not behave exactly as predicted in FEA.

Having finished this iteration of the design, the part can be fabricated using the methods selected in step 3.

7.9. Step 9 – Testing and validation of final geometry

Characterisation testing should provide insights into the performance of the finalised auxetic component and ensure it meets all the application's core requirements. Some possible test methods are referenced in Section 6.

If an FEA study has been performed on the full modelled part, it may be validated using this experimental data. This validated FEA can then be used to try out test cases that may be hard to setup experimentally. It is useful to compare the properties of this component incorporating auxetic structures with an equivalent conventional part. This will show what benefit has been gained using auxetic structures.

7.10. Step 10 – Check final lattice behaviour

Results of these tests will decide whether the design is suitably finished or if another design iteration is required. Note that it may not be necessary to redo all the design steps during iteration despite what Figure 23 suggests. For example, if component's failure is expected to be due to how the auxetic lattice is integrated into the component then only steps 7-9 will need to be redone. If the core requirements have all been met and the component performs well, then the design can be considered finished.

7.11. Step 11 – Redesign and develop unit cell if necessary

If the previous iteration of a design has failed to fulfil the application requirements, then any design insight gained can be carried onto the next iteration. It is suggested that the behaviour of the unit cell in the current iteration is examined and used to re-design and develop the selected unit cell further to suit the application. At this point the manufacturing method and material selected should be considered again in case an improvement can be made by changing them. Once a new design plan is realized, the new iteration can begin at step 6. This will allow the unit cell to be optimised again using new knowledge and potentially different materials before being tested and characterised. Alternatively, the current unit cell could be scrapped entirely, and the new iteration begun at step 3.

8. Other considerations

There are several other considerations that may not fit in with the standard design workflow but are worth mentioning:

8.1. Multi-material applications

One area of interest is the potential for using multi-material additive manufacturing in auxetic structures. The auxetic behaviour of unit cells depends on parts of the cell flexing or hinging, and other parts of the unit cell remaining relatively rigid. Traditionally both parts of the unit cell would be made out of the same material, but now the effect of mixing flexible and more rigid material to alter the hinging effect has been investigated [76]. The modified cells can be seen in Figure 25.

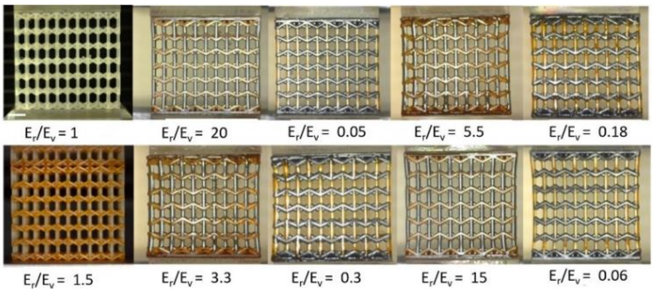


Figure 25. Multi-material re-entrant honeycomb lattices with varying re-entrant strut Young's modulus E_r and vertical strut Young's modulus E_v. [76].

They reportedly exhibit the highest negative Poisson's ratio where the re-entrant struts are most flexible, and the vertical struts are stiffest. Varying the material properties in this way allows for tuning of auxetic structures separate from the geometric parameters. There is also the possibility of using multi-material manufacturing on the lattice level rather than at the cellular level as seen in Figure 9.

8.2. Graded Lattices

It may be possible to improve the performance of auxetic structures by introducing a grading in the lattice. In theory a grading could be applied to different parts of the unit cell geometry to modify different mechanical properties and alter the auxetic behaviour throughout a lattice. An example of how geometry changes can tailor mechanical properties is in Section 3. Material may also be graded as seen in the design of sandwich structures with alternating layers of hard and soft material by Bodaghi et al. [31] in Section 4.1. The design of a crash box in Section 4.1.1 provides an example of an auxetic lattice being graded to the benefit of an impact absorbing application. Figure 26 shows an example of a graded auxetic lattice structure.

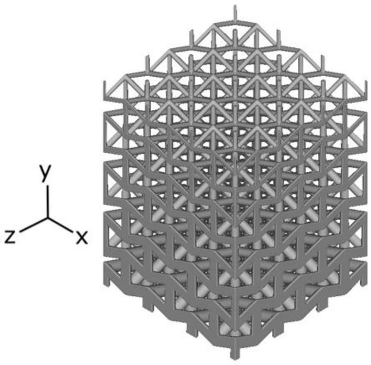


Figure 26. 3D re-entrant unit cell auxetic lattice graded so that bottom struts are thicker and top struts are thinner.

8.3. Hierarchal structures

Hierarchal structures can be made that combine different auxetic structures together, or the same structure in different layouts. These allow for a structure with properties that depend on the combined properties of the systems they are made up, or how the systems are connected. Figure 27 shows a set of different hierarchical systems made up of the same basic auxetic system connected in different ways. In the work done by Gatt et al. [77] the two level system in a-ii) of Figure 27 was analysed through simulations and found to have a negative Poisson's ratio which varied based on the stiffness of the links in the level 0 and level 1 systems. In a similar line of thinking, conventional cells may be combined with auxetic cells to suit an application [13].

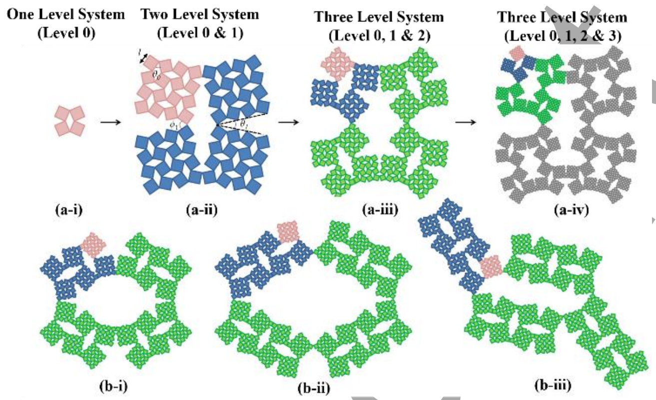


Figure 27. Various hierarchical systems based on the same auxetic rotating rigid units mechanism [77].

8.4. Axisymmetric structures

There are applications where the auxetic structure may be loaded in a single direction, such as when acting as an energy damper. A technique has been developed for creating axisymmetric auxetic structures that are well suited for being loaded in a singular direction with a circular contact area [78]. The process allows existing 2D re-entrant unit cells to be used and rotated to form auxetic cylinders. Figure 28 illustrates the process.

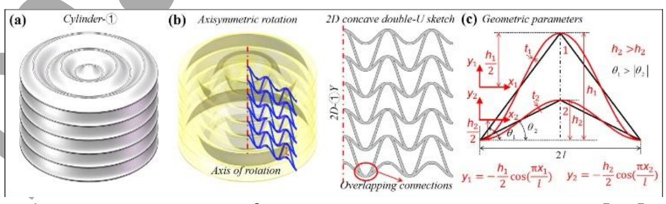


Figure 28. Creation of axisymmetric auxetic structure [78].

8.5. Loading of cellular structures

When using auxetic cellular structures, the load should be applied across several unit cells and struts should be prevented from being loaded individually. This can be done by both making the unit cells smaller to increase the number of cells in contact and using a covering sheet that spreads the load more evenly. Examples of covering sheets being used can be seen in Figure 2(e) and Figure 2(h). Cells may be left exposed in areas where a load is not being applied and doing this may even allow better cellular motion, but any cells that are under an applied load should be covered.

9. Gap analysis

While multiple auxetic literature reviews [2,3,23,79] discuss various theoretical applications for auxetic structures, only some of these end-use applications have had their concept proven. In addition, it can be seen from examples in Section 4 that much development of auxetic applications is not market ready yet.

While it is hoped that the design workflow outlined in this paper will help to bring market ready auxetic applications closer to a reality, there is much more work that will need to be done to support it. One thing which is currently lacking is a structured approach for selecting an auxetic unit cell. It is likely this process could use a set of standardised property tables that characterise the range of properties each unit cell can be designed to have. This would require additional experimental testing/FEA to fill out the unit cell property tables in a standardised manner. Alongside this, a general guide on characterisation testing of auxetic structures could be developed to ensure that properties such as Poisson's ratio and how it varies with strain can be accurately captured experimentally.

There is limited experimental research done on the fatigue performance of auxetic structures. Lvov et al. [80] showed that auxetic structures fabricated using selective laser melting (SLM) outperform their non-auxetic counterparts under fatigue compressive loads. Lvov et al. [81] also experimentally showed through low cycle fatigue tests up to 500 cycles that auxetic structures can be used as dampers due to their good energy absorption.

Before being used in applications that require cyclic loading, a standardised set of fatigue testing experiments should be created. These would have to be performed so that the lifetime of auxetic structures could be accurately predicted.

Currently a large portion of the research focuses on additively manufactured polymers due to the ease of manufacturing [2]. Experimenting with a wider range of materials would lead to a larger variety of potential applications. Metallic structures would be a better fit for structural strength requirements. Ceramic structures could further the development of auxetic piezoelectrics.

As auxetic cells can be scaled to any size and retain their properties, a micro-scale auxetic lattice could benefit many small-scale applications. However, aside from the manufacturing of auxetic foams, there seems to be few examples of auxetic structures being micro-manufactured.

10. Conclusion

By outlining different considerations that must be accounted for during the process and analysing them through the lens of a design engineer, the different steps of the design process have become clear in this work. These steps have then been drawn together into a general design workflow as outlined in section 8.

There are a wide variety of ways in which auxetics can add to an application and Section 3 shows some applications that have been explored. Some of these applications are more promising than others, specifically the ones that directly rely on the negative Poisson's ratio to solve the challenges of an application in an entirely new way. Besides unit cell optimisation, the performance of an auxetic structure may be improved using graded lattices in certain applications as seen in Section 2.2.

The biggest hurdle to an effective auxetic design process is the lack of a standardised method for selecting the best unit cell for an application. It has been proposed that further work should focus on creating a set of standardised property tables for each commonly used unit cell so that in the future designers could easily compare them to find the best fit for their application. This in conjunction with a standardised design workflow which would allow designers to effectively create auxetic structures optimised to suit their application and allow the theorised beneficial properties of auxetics to be fully realised.

When an application is relying on the secondary properties of auxetic structures (see Section 2), its mechanical properties may be directly comparable to conventional materials. A solid block of conventional material may provide better mechanical properties on a per volume basis than an auxetic cellular structure but be denser and heavier overall. This means auxetic materials might not be suitable for applications where weight is not limited, part volume is restricted, or extreme mechanical properties are required. We can conclude that from a design point of view auxetic materials benefit most in applications that require good secondary material properties at a low density/weight, or where the application depends on the primary properties of auxetics rather than secondary ones.

11. References

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