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Review Article

Review of Mechanics and Applications of Auxetic Structures

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One of the important mechanical properties of materials is Poisson's ratio, which is positive for most of the materials. However, certain materials exhibit "auxetic" properties; that is, they have a negative Poisson's ratio. Thus auxetic and non-auxetic materials exhibit different deformation mechanisms. A specific microscopic structure in the auxetic materials is important for maintaining a negative Poisson's ratio. Based on their distinct nature auxetic materials execute certain unique properties in contrast to other materials, which are reviewed in this paper. Thus auxetic materials have important applications in the biomedical field which are also a part of this review article. Many auxetic materials have been discovered, fabricated, and synthesized which differ on the basis of structure, scale and deformation mechanism. The different types of auxetic materials such as auxetic cellular solids, microscopic auxetic polymers, molecular auxetic materials, and auxetic composites have been reviewed comprehensively in this paper. Modeling of auxetic structures is of considerable importance and needs appropriate stress strain configurations; thus different aspects of auxetic modeling have also been reviewed. Packing parameters and relative densities are of prime importance in this regard. This review would thus help the researchers in determining and deciding the various aspects of auxetic nature for their products.

1. Auxetic Structures

From the daily life experience, when the material is stretched, the material not only becomes longer in the direction of stretch but also becomes thinner in cross-section. The behavior of the material in this case under deformation is governed by one of the fundamental mechanical properties of material, that is, Poisson's ratio [1].

Poisson's ratio (ν) of a material is the ratio of the lateral contractile strain to the longitudinal tensile strain for a material undergoing tension in the longitudinal direction; that is, it shows how much a material becomes thinner when it is stretched. Therefore, most of the materials have a positive ν. In case of counterintuitive behavior of auxetic material, it undergoes lateral expansion when stretched longitudinally and becomes thinner when compressed [2, 3].

The network is deformed by hinging of the ribs forming the network in case of honeycomb structure. It is observed that, for individual cells having the conventional hexagonal geometry, the cells elongate along the y-axis and close up along the x-axis in response to stretching the network in the y-direction, giving a positive ν. By maintaining the same deformation mechanism (rib hinging) but modifying the honeycomb cell geometry to adopt the reentrant structure, the cells of the network now undergo elongation both along and transverse to the direction of applied load (in Figure 1). Hence the reentrant honeycomb deforming by rib hinging is an auxetic structure. Generally this structure is anisotropic; that is, the value of ν when loaded along the x-direction (ν_{xy}) differs from that when loaded along the y-direction (ν_{yx}). The theory of elasticity is scale-independent and so the structure that is deforming may be at a macroscopic or microstructural level, or even at the mesoscopic and molecular levels [2, 3].

All common materials have positive ν; that is, the materials contract transversely under uniaxial extension and expand laterally when compressed in one direction. For linear elastic materials that are isotropic negative Poisson's ratio cannot be less than −1 or greater than 0.5. This is due to empirical and stability considerations related to work-energy factors, so the bulk and shear modulus have positive values [4]. For auxetic materials, these limits are different.

1.1. Deformation Mechanism. Reentrant cell geometrical parameters, that is, H, L, and λ, can even change the sign

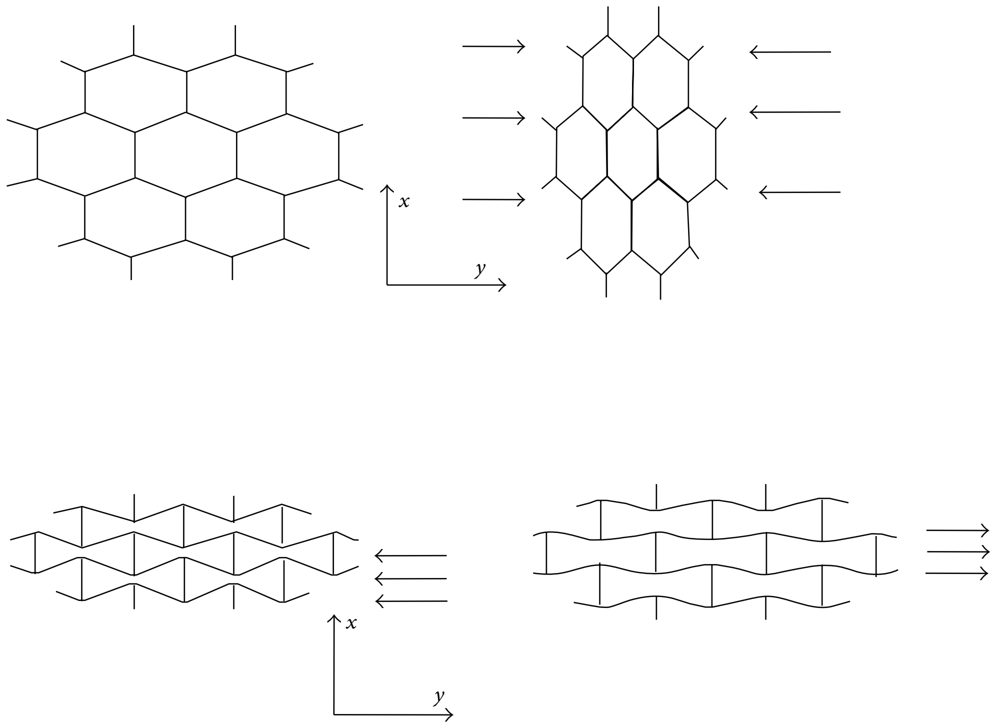


FIGURE 1: Nonauxetic (honeycomb) and auxetic (reentrant) structure deformation mechanism [2, 3].

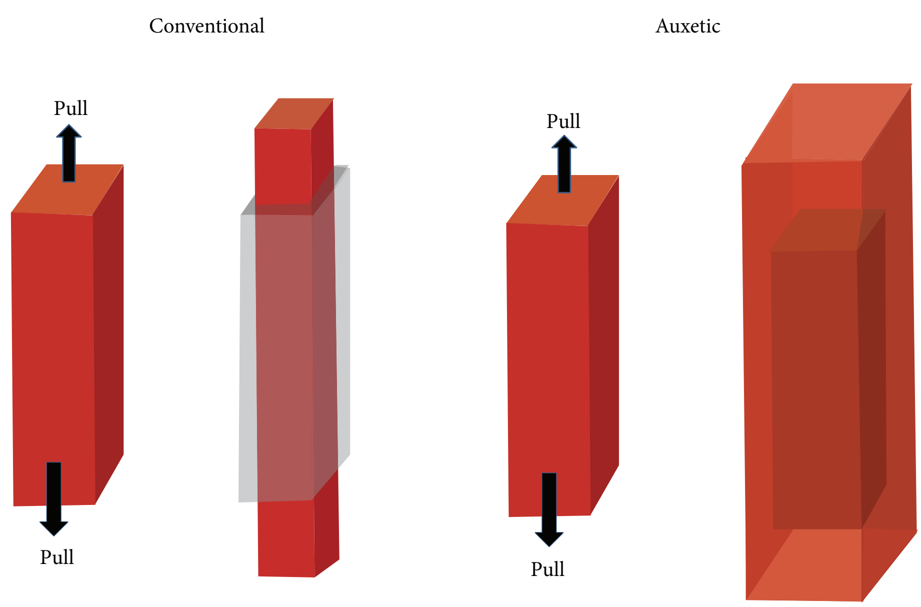


FIGURE 2: Deformation of auxetic and conventional materials [28].

of Poisson's ratio from negative to positive, when auxetic honeycombs bear a Y-direction tensile loading or an X-direction compressive loading, where H is the vertical length of the cell member, L is the inclined length of cell member, and λ is the angle between undeformed inclined cell member and X-axis (in Figures 2 and 3). In other words, the magnitude of Poisson's ratio decreases significantly at high strain when the auxetic honeycomb is compressed in X-direction loading or stretched in Y-direction loading, while it increases significantly at high strain when the auxetic honeycomb is stretched in X-direction loading or is compressed in Y-direction loading [5].

In all of the auxetic materials there is a specific microstructure that is vital to creating a negative ν, deformation mechanism like rib hinging, bending or stretching, and rotating, and so forth. Their length scale varies from

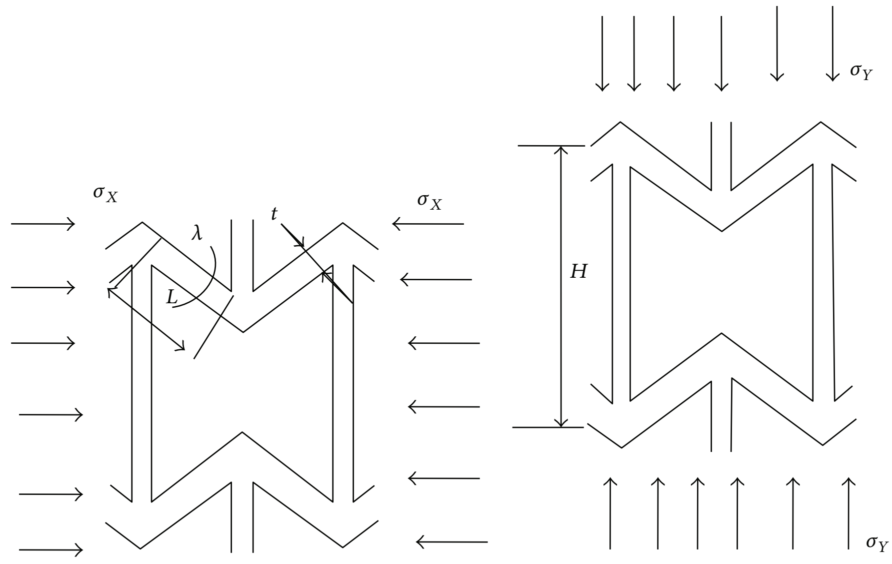


Figure 3: Cell deformation by inclined cell member bending, (a) loaded in X-direction, (b) loaded in Y direction [5].

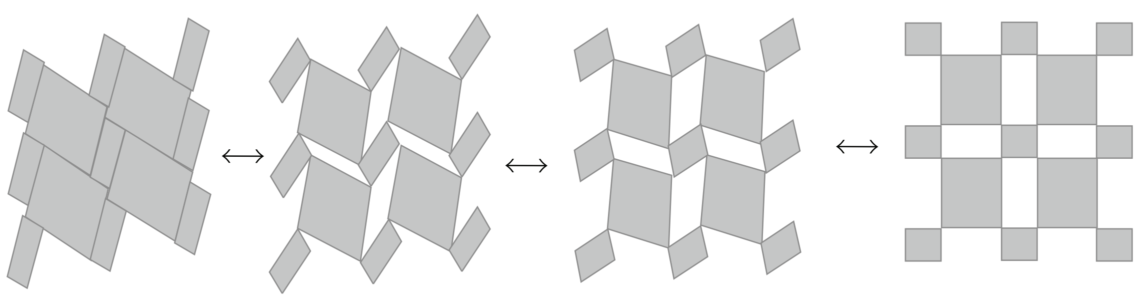


Figure 4: Rigid rectangles connected together at their vertices through hinges and deforming by rotating [29].

the nanometer for crystal structures to tens of meters for the key-brick structures [6].

It has been found that the ν is a scale independent property; that is, the deformation mechanism can operate at any scale ranging from the nanolevel (molecular level) to the macroscale. In some cases, the presence of auxetic behaviour in very different systems has been explained by using the same deformation mechanism, for instance, "the rotation of rigid units model has been used to account for the auxetic behaviour in materials ranging from silicates and zeolites (where the auxetic effect is due to nanostructure of the materials) to polymeric foams (where the auxetic effect is due to features at the micromillimeter scale) and macrostructures [7].

1.2. General Properties of Auxetic Structures. The auxetic materials offer some unique properties in comparison with the common materials. Classical elasticity theory predicts that auxeticity of materials should lead to enhancements in certain mechanical properties, such as increased plane strain fracture resistance and increased shear modulus, indentation resistance, fracture toughness, and acoustic response compared to conventional materials [8].

Auxetic materials are of interest because of the novel behaviour they exhibit under deformation and also because many other materials properties can be enhanced as a result of having a negative ν. In the case of an object impacting a nonauxetic material, the material immediately below the impact flows away in the lateral direction, leading to a reduction in density and, therefore, a reduction in the indentation resistance of the material. For an auxetic material, on the other hand, material flows into the vicinity of the impact as a result of lateral contraction accompanying the longitudinal compression due to the impacting object. Hence, the auxetic material densifies under the impact in both the longitudinal and transverse directions as shown in Figure 5, leading to increased indentation resistance [2, 3].

Auxetic ultra high molecular weight polyethylene (UHMWPE) exhibits enhanced indentation resistance by up to a factor of three when compared with conventional UHMWPE and enhanced attenuation of ultrasonic signals [2, 3].

Auxetic materials exhibit the very unusual properties of becoming wider when stretched and narrower when squashed; that is, they have negative Poisson's ratios. Apart

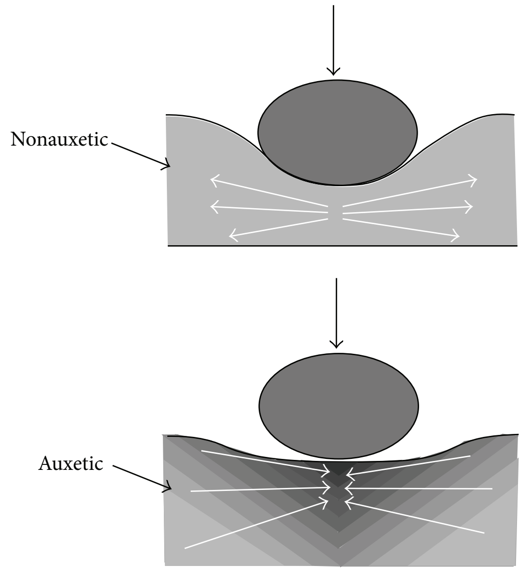


Figure 5: Indentation resistance of nonauxetic and auxetic materials [2, 3].

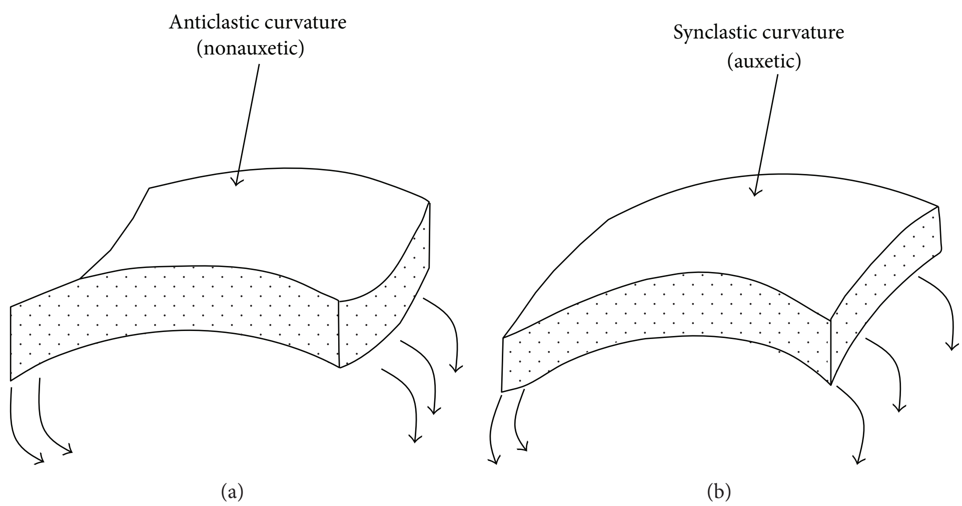


Figure 6: (a) Saddle-shaped surface of the conventional material and (b) auxetic dome-shaped doubly curved surface [2, 3].

from the pure scientific interest of having materials showing such an unconventional property, a negative Poisson's ratio gives material several other beneficial effects such as increased shear stiffness, increased plane strain fracture toughness, and an increased indentation resistance. These properties make auxetics superior to conventional materials for many practical applications [9].

It is observed that auxetic materials possess attractive acoustic properties, and it is found that at frequencies up to 1600 Hz auxetic forms of polymeric and metallic foams possess enhanced acoustic absorption when compared with conventional materials. A further study examined the ultrasonic attenuation of the auxetic UHMWPE compared with a microporous positive ν form of UHMWPE of equivalent density and compression moulded UHMWPE [10].

The auxetic materials have a natural tendency to form dome-shaped doubly curved (synclastic) surfaces (in Figure 6), unlike conventional materials which tend to form saddle-shaped surfaces [2, 3].

The application of using cork, which is a material with nearly zero Poisson's ratio, for sealing wine bottles, is well known. Another class of applications of auxetics is based on the sound absorbing properties of auxetic materials, which make them interesting for both civil and military applications. Furthermore, several investigations speculate auxetic behaviour in biomechanics, like for the spongy part of the bones, with obvious implications for the efficient design of prostheses in cork and in skin [11].

1.3. Applications of Auxetic Structures. In the biomedical field auxetic microporous and cellular materials have potential, like a dilator for opening the cavity of an artery, or similar vessel has been described for use in coronary angioplasty and related procedures (in Figure 7). The artery is opened up by

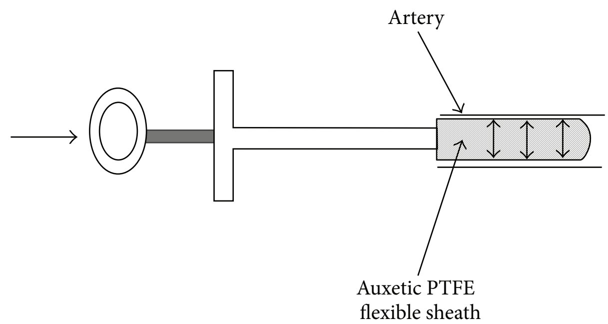


Figure 7: Dilator employing an auxetic end sheath [2, 3].

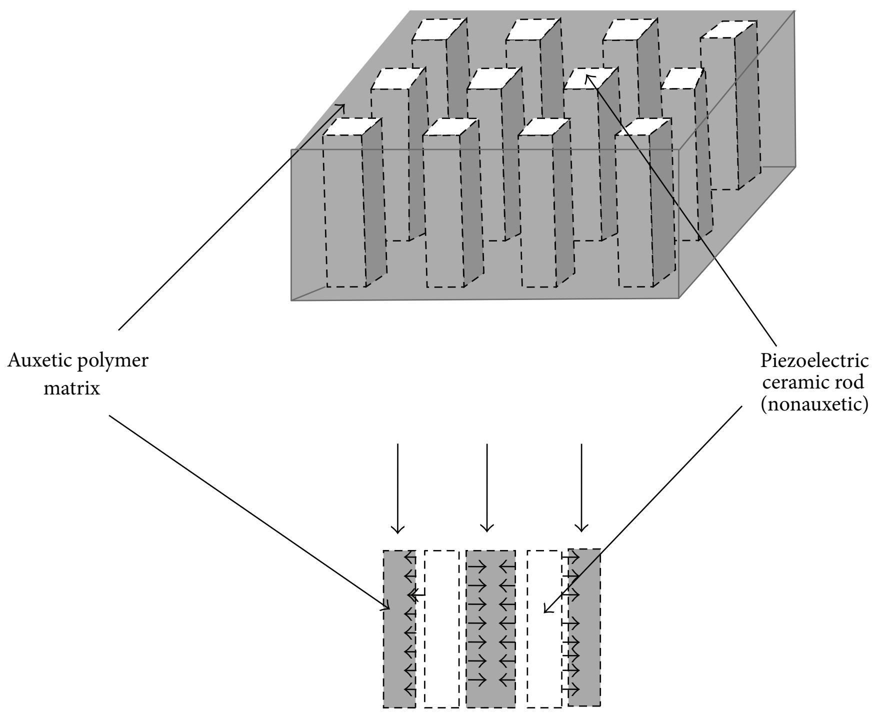


Figure 8: Piezocomposite device geometry, consisting of nonauxetic piezoelectric ceramic rods interspersed within an auxetic polymer matrix for enhanced device sensitivity [2, 3].

lateral expansion of a flexible auxetic polytetrafluoroethylene (PTFE) hollow rod or sheath under tension [2, 3].

An interesting potential application of auxetic material lies in the manufacturing of smart bandages and smart filters; that is, one of the properties of auxetic materials is that once you apply stress to them, when you pull them, their pores become larger. If a filter is made from these auxetic foams, just by stretching the foam in one direction, the pores become larger. With such uniform enlargement of the pores an adjustable filter can also be made, which can range from very small holes to very large holes. Auxetic foams can also be impregnated with medication which would work as follows: for a swollen wound, the effect of the wound pushing against such a dressing would be to release the medication, and this will happen in a manner depending on how much it is being pulled [12].

In sensor and actuator applications functional composite materials are used like piezoelectric composites consist of piezoelectric ceramic rods within a passive polymer matrix and are used in medical ultrasonic imagers and hydrophone receivers of naval sonar. Recently, they are designed to optimize the performance of these piezocomposite devices which have shown that an auxetic polymer matrix is preferred to a nonauxetic matrix for several reasons. Firstly, in response to a compressive load exerted on the surface of the device the auxetic polymer matrix contracts laterally. This allows free lateral expansion of the ceramic rods, leading to enhanced electromechanical coupling of the device, which is crucial for overall device performance. Secondly, for a device designed to respond to hydrostatic pressure, "a nonauxetic polymer matrix converts a compressive planar stress into a tensile longitudinal stress, which acts to diminish the incident vertical compressive stress. An auxetic matrix, on the other hand, converts the compressive planar stress into a compressive longitudinal stress and therefore reinforces the incident vertical compressive stress (in Figure 8). Another

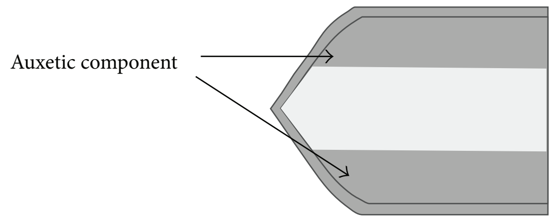
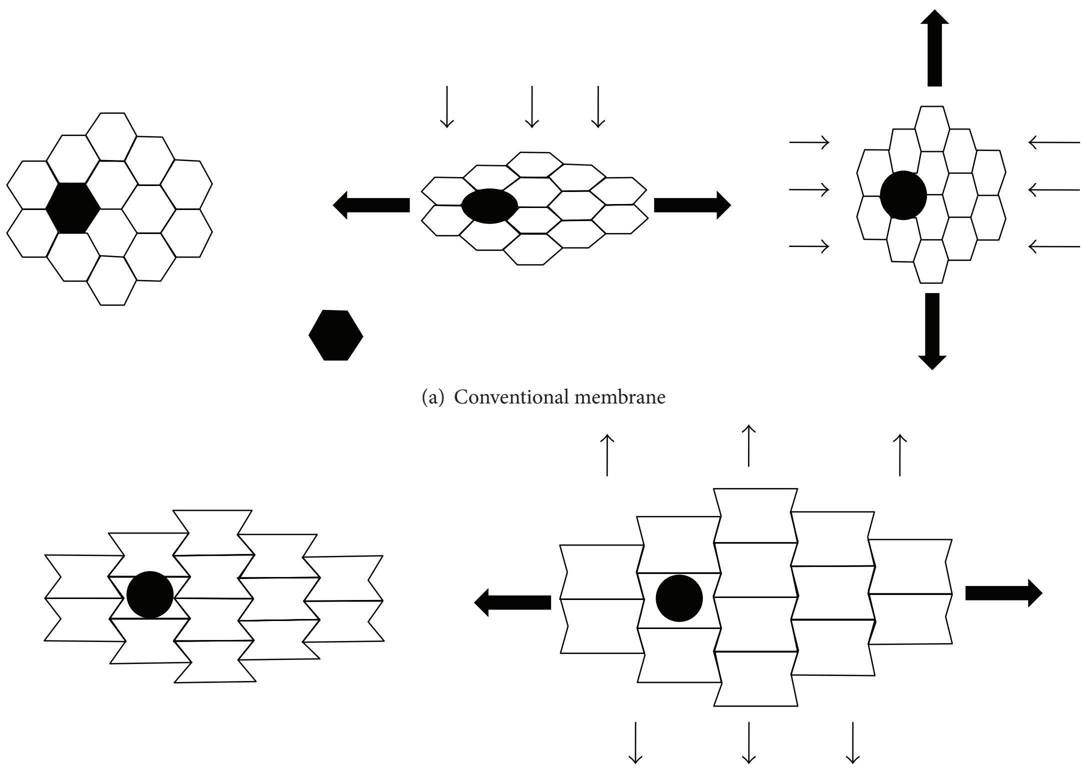


Figure 9: Bullet or shell containing auxetic and nonauxetic components [2, 3].



(a) Conventional membrane

(b) Auxetic membrane

Figure 10: Particulate defouling capabilities of (a) nonauxetic honeycomb membrane filters and (b) filters having auxetic membrane [13].

benefit of an auxetic matrix is due to the concomitantly high shear modulus relative to bulk modulus. This enables efficient conversion of incident stresses on the polymer to lateral stresses acting on the ceramic rods, thereby improving the acoustic-to-electrical energy conversion" [2, 3].

A number of other technological applications for auxetic materials are actively being pursued, like a bullet or shell in which one component is made of auxetic material such that the overall projectile has Poisson's ratio of zero. In this case the movement of the projectile down a barrel is facilitated by a reduction in lateral expansion due to the auxetic component under the thrusting force (in Figure 9). Auxetic materials have also been identified as candidate materials for use in electromagnetic launcher technology, where a reduction in mass is required in the future for many components, which may be used to propel such projectiles. The intended recipient of the projectile might benefit from a bullet-proof vest and other personal protective equipment formed from auxetic material due to the impact property enhancements [2, 3].

The potential to create filters by polymeric auxetic structures, with an enhanced pore size and with shape tunability, can offer potential ways of overcoming the problems of filter systems with conventional materials, like reduction in filtration efficiency and the development of a pressure drop across the filter because it becomes blocked. The conventional honeycomb membrane filter pores undergoing uniaxial stretching extend along the stretching direction but close up in the lateral direction. In this case, a particle blocking such a pore cannot be transmitted through the pore when the membrane is stretched since the effective pore size decreases, while the pores of an auxetic honeycomb membrane filter however, open up in both the lateral direction and the direction of the applied tensile load, (in Figure 10), and therefore particulate defouling is possible [13].

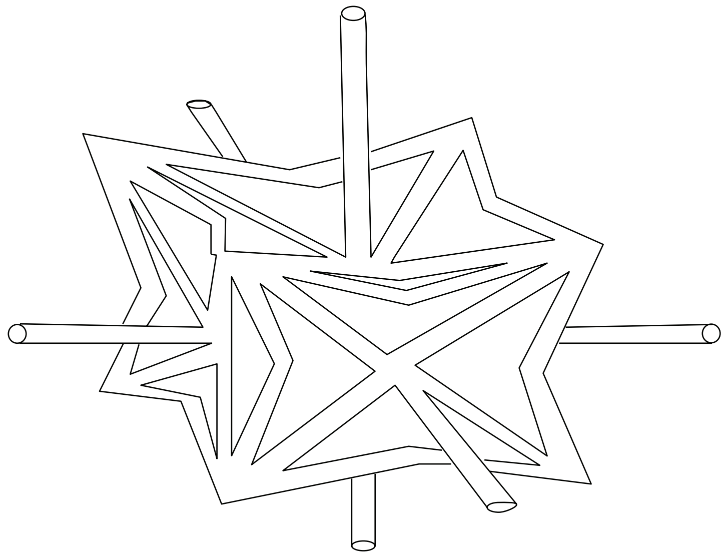


Figure 11: Reentrant unit cell [8].

1.4. Types of Auxetic Structures and Their Mechanical Characteristics. There are many types of auxetic structures which are currently present and vary from each other according to their structural difference, deformation mechanism, and scale. A range of auxetic materials have been discovered, fabricated, synthesized, and theoretically predicted, such as polyurethane and polyethylene foams, microporous polytetrafluoroethylene (PTFE), microporous ultra high molecular weight polyethylene (UHMWPE) and polypropylene (PP), highly anisotropic composites, laminates, and several types of rocks with microcracks. Naturally occurring molecular auxetic α-cristobalite and zeolites were also predicted to process the counterintuitive property by calculation or simulation [8].

1.4.1. Auxetic Cellular Solids. One stage thermomechanical process is used to prepare auxetic polyurethane foams composed of reentrant cells, which include triaxial compression of conventional open cell foam into a mould, heating of the specimen slightly above the softening point of the foam material, and then cooling and relaxation [8].

A more controlled multistage processing technique was also tried, which separated the transformation process into several stages, by minimizing the risk of surface creasing and producing more homogenous specimens [14]. Recently, polyethylene foams were also transformed into reentrant microstructures through the thermomechanical processing and attained the auxeticity. "The key to achieve auxeticity in reentrant foams lies in their microarchitecture (in Figure 11), where the ribs of each auxetic foams' cell permanently protrude inward compared with conventional foams' convex cell structure" [8].

The mechanical properties of auxetic polyurethane foams have been tested with regard to antivibration properties. These auxetic characteristics would be useful in the manufacture of gloves for workers to protect them from the damaging effects of mechanical vibrations. In this study the static and dynamic characteristics of auxetic polyurethane foams were analyzed. It was found that the auxetic foams exhibited an increase in stiffness in response to compressive loading. In the same study, an elastic, linear finite elemental analysis also suggested a decrease in compressive stresses where auxetic foams were concerned, in comparison with nonauxetic polyurethane foams [15].

The process by which conventional, reticulated, positive ν foams are converted into auxetic foams involves volumetrically compressing the foams, heating beyond the polymer's softening temperature, and cooling whilst remaining under compression (in Figure 12). This process buckles the cell ribs inwards, creating a reentrant cellular geometry. It is believed that under tension, the cells unfold outwards towards their original shape, generating an expansion of the bulk specimen and therefore a negative ν. This unfolding process reverses under compression. While heating under compression of the foams to convert from conventional to auxetic foams, the foams are twice temporarily removed from the oven and their containers. Once removed, they are longitudinally stretched by hand and quickly returned to the containers and oven. This stretching episode, typically repeated twice, is just to ensure that the cell ribs do not stick to each other. Inevitably during the volumetric compression of the foams, creases or wrinkles appear in the surface of the foam. It is found that the location of these creases or wrinkles corresponds to the more deformable areas noted following conversion to auxetic behavior [16].

Conventional honeycomb structures can be fabricated into reentrant structures. The negative ν in the cell plane of the reentrant honeycomb structure has a value that depends upon the reentrant angle of the cell rib. The honeycomb ceramics with auxeticity can be produced by the extrusion of ceramic pastes through polymer dies produced by rapid prototyping (selective laser sintering) and designed with CAD technology [8]. Most of the materials have a microstructure that induces a negative Poisson's ratio at a macroscale. For instance, the microstructure of auxetic foam is the three-dimensional

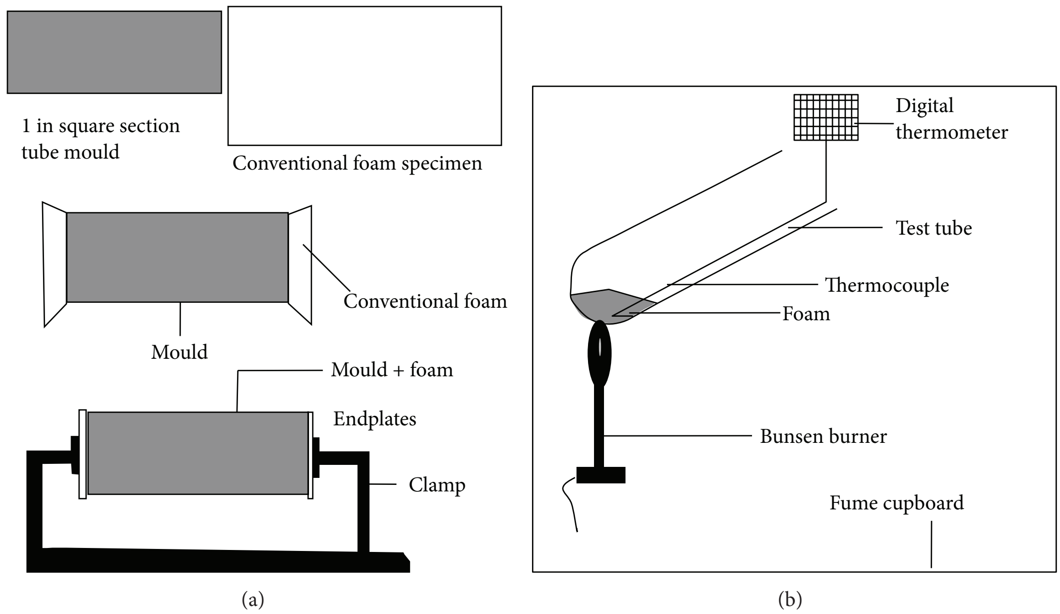


Figure 12: (a) 3D compression of conventional foam specimen by inserting into the square section tube and (b) heating of the foam inserted into tube at 200°C [19].

array of discrete ribs. These ribs interact together so that a statistically large sample (macroscale) displays a negative Poisson's ratio [6].

In a comparison between regular and auxetic honeycomb structures, it has been concluded that matrix material properties do not make a significant difference. There is a decrease in Poisson's ratio with an increase in volume fraction in regular structures. Young's modulus increases with the volume fraction. However, in auxetic (reentrant) honeycomb structures, the ν value is dependent on the inverted angle of the cell. There is a decrease in Young's modulus with an increase in the inverted angle [17].

Laser ablation technique was used recently to fabricate auxetic polymeric honeycomb membranes with cell dimensions of ~1 mm, and these have been proven to provide improved membrane filter cleaning and particulate size selectivity capabilities due to the unique pore variation properties of auxetic materials. Active and passive smart filters based on auxetic materials can be envisaged to give improved filtration process efficiency whilst reducing the number and frequency of filters to be replaced, leading to reduced plant down-time and waste minimization in the form of a reduction in the number of spent filters [2, 3].

It is found that the cell size makes only a minor contribution to the mechanical properties of foam; a much more significant contribution is attributed to the cell shape. For the isotropic properties the cells should be equiaxed. Three different types of foam cell structure are as follows: open cell, closed cell, and reticulated foams. The distinctions between these three foams are that closed cell foams have a membrane of variable thickness covering each face of the cell. In open cell foam, most of these membranes are perforated, and in reticulated foams the membranes are removed by chemical means or by heat treatment [18, 19].

Recently, a new methodology was proposed by [7] which is called "Empirical Modelling Using Dummy Atoms" (EMUDA), which is particularly suitable for studying the properties of two-dimensional hexagonal honeycombs deforming through stretching or hinging of the rib elements, and it correctly predicts the magnitudes of Poisson's ratios (in Figure 13). They presented the potential for auxetic behaviour of a novel class of structures which can be described as "connected stars" as they contain star-shaped units which are connected together to form two-dimensional periodic structures. A macrostructure which has been studied for its auxetic properties is the hexagonal reentrant honeycomb constructed from arrow-shaped building blocks. However, the reentrant hexagonal honeycomb is not the only tessellate which can be constructed from arrows. Star-shaped building blocks which have rotational symmetry of orders $n = 3$, 4, and 6 may be built by connecting $n = 3$, 4, and 6 arrows in such a way that the arms of the arrows form stars.

This study is based on an analysis through the "force field molecular modeling simulations (EMUDA). Several conclusions have been drawn based on this technique. It has been shown that star shape containing systems with the rotational symmetry of orders 4 and 6 show auxetic behavior to a greater degree when compared with systems that have a rotational symmetry of order 3. Also, the stiffness of the hinges connecting different rod structures affects the overall Poisson's ratio. An alteration in the hinge stiffness also has a different effect on different systems.

1.4.2. Microporous Auxetic Polymers. The microporous PTFE microstructure consists of an interconnecting network of nodules and fibrils, whose cooperative interaction under an applied load produces the auxeticity (in Figure 14). Soon after, UHMWPE and PP were produced through compaction,

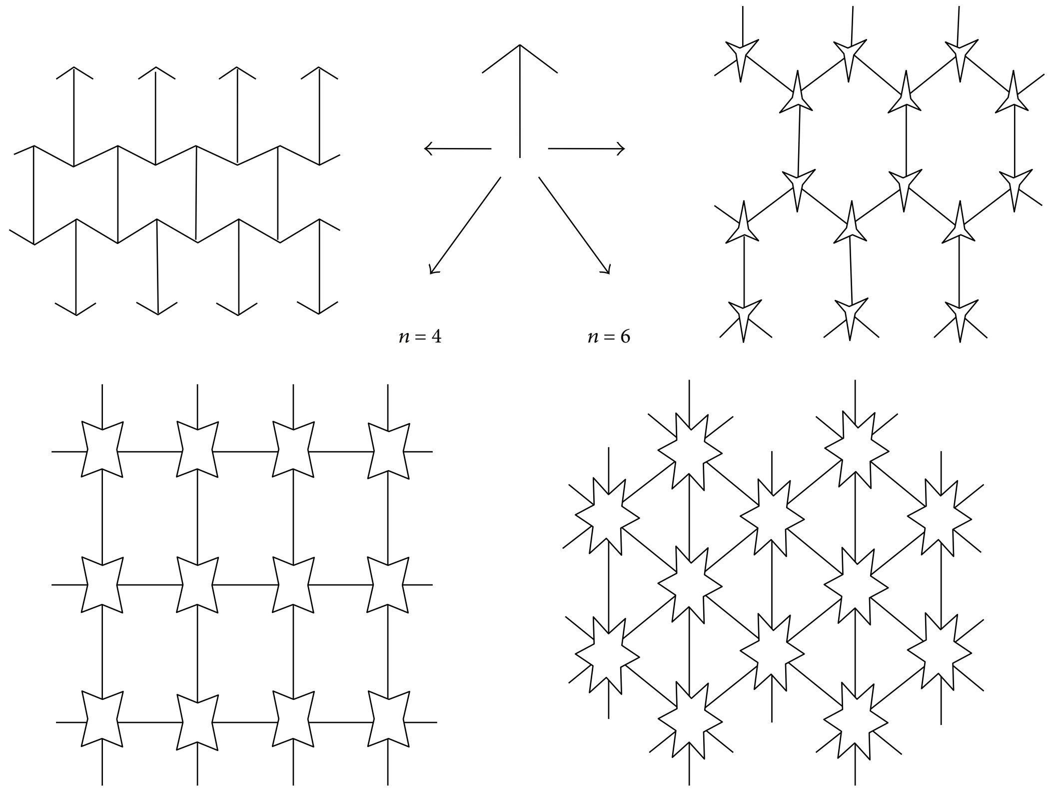


Figure 13: Various tessellations which can be constructed from "arrows" [7].

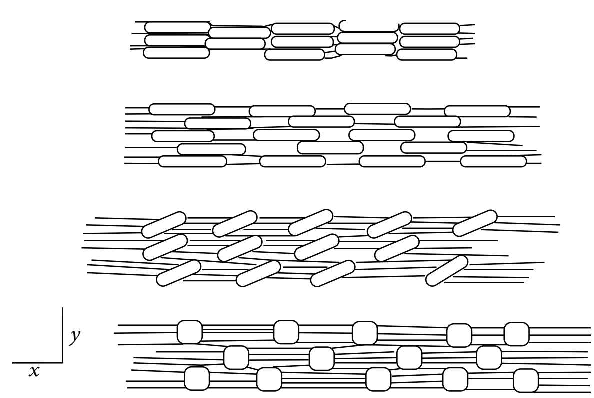


Figure 14: : Microporous PTFE undergoing tensile loading in the x-direction, tension in fibrils causing transverse displacement of nodes and lateral expansion [8].

sintering, and extrusion route or by only sintering and extrusion processing to achieve auxeticity. This is due to cooperative interaction of nodules and fibrils which produces an expansion in the transverse direction and at the same time the fibrils cause the nodules to be pushed apart [8].

Morphology studies showed that the auxetic property in PTFE is due to the microstructure rather than any intrinsic property of PTFE itself. The microstructure consists of nodules interconnected by fibrils. UHMWPE has been processed by a novel processing route developed recently, which has three stages, compaction of UHMWPE powder in heated barrel, followed by sintering of the compacted rod, and finally, immediate extrusion of the sintered rod through a die [2, 3].

In microporous polymers auxetic behaviour was first observed in a particular form of PTFE, and soon after for the fabrication of auxetic cylinder of UHMWPE, polypropylene (PP), and nylon, thermal routes were used. It was observed that the processing temperature is the most critical parameter governing the presence of auxeticity, and other parameters such as die geometry, sintering time, structural integrity, and extrusion rates were also shown to have some effect on the

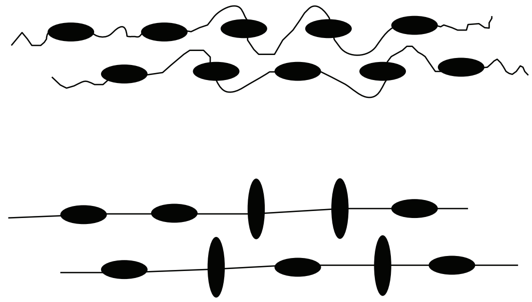


Figure 15: Arrangement of laterally attached rods in a main chain liquid crystalline polymer [8].

auxeticity of the material. The new form of microporous PP is formed as PP films using the same thermal processing technique involving melt spinning in an extruder and the same PP powder, but different die geometry (i.e., from hole orifice to slit orifice and from circular die-head cross-*sectionally* to rectangular). Thermal characteristics of PP powder were attained by differential scanning calorimetry (DSC), such as melt onset temperature and peak melting temperature. For the characterization of the PP powder in terms of particle size distribution, surface roughness, and shape or dimensions, scanning electron microscopy (SEM) was used. The extruder used was employing an Archimedean screw mechanism, five temperature zones, thermocouples, and die slot with slit orifice. Characterisation of the mechanical properties of auxetic PP films was carried out by video extensometry to measure the strains across both the length and the width during deformation of the PP films by both Instron tensile testing and Deben microtensile testing equipment [20]. An interesting observation during this study was the change in auxetic behavior (i.e., a change in Poisson's ratio, with a change in the strain values). The film exhibited auxetic characteristics up to strain values of ~1%. After this, a transition from negative to positive Poisson's ratio (auxetic to nonauxetic behavior) was seen. A positive Poisson's ratio strains greater than 1% were seen. For the auxetic polypropylene films, mentioned earlier, a higher Young's modulus has been shown in the nonauxetic film as compared to the auxetic film.

1.4.3. Molecular Auxetic Materials. Polymers with special microstructures and special inorganic crystals like silicon dioxide, zeolites, and elemental metals are the auxetic molecules. It is a simple molecular design approach based on site-connectivity driven rod reorientation in main chain liquid crystalline polymers to achieve auxetic behaviour (in Figure 15). Under a tensile force, the extension of the flexible spacers in the polymer main chain will force the laterally attached rods from a position roughly parallel to the tensile axis to a position normal to it and push the neighbouring chains further apart [8].

Another molecular network is twisted-chain auxetics, in which auxetic behaviour arises due to a soft shear deformation mode for helical polyacetylene chains formed from adjacent chains in a coupled polydiacetylene chain network [2, 3].

Molecular auxetics basically address overall weaknesses that are inherent in auxetic microstructures. There is no restriction of scale with regard to auxetic properties: therefore, it is possible to design auxetic materials on the molecular scale. Thus changing the molecular structure gives a high degree of control over the overall auxetic properties, by the incorporation of molecular entities that cause the structure to exhibit auxetic behavior. The advantage that these materials will have over the microscale man-made and natural auxetics is that these materials possess an inherent set of tailorable mechanical characteristics ([21], n.d.).

Studies have been conducted to investigate the stress-strain response with reference to auxetic behavior in liquid crystalline elastomers (LCEs). It has been found that, with an increased percentage of cross-linkers, the LCEs show an increased modulus and a shorter polydomain to monodomain (P-M) plateau. Stress-strain observations were made with the simultaneous determination of Poisson's ratio. Typically, it was seen that Poisson's ratio had risen to a maximum point at around 50% strain and then decreased with greater strain. For achieving auxetic response, shorter spacers, nematic mesophase long transverse rods along with higher strain values have been proposed [22].

Further Auxetic Geometries: The Rotating Squares and Parallelograms. A mechanism to achieve negative ν is based on an arrangement involving rigid squares connected together at their vertices by hinges (in Figures 17 and 18). As each unit cell contains four squares, each square contains four vertices, and two vertices correspond to one hinge [9].

It is found that this type of behaviour may also be achieved from the more general case involving hinging parallelograms or in the networks built with different sized squares [9]. The rotating squares design has been studied with regard to potential oesophageal stenting applications. Mechanical tests on polyurethane samples with the rotating squares geometry revealed that there was a 4 mm extension for a 2.5% strain, in response to a uniaxial 500 g tensile load. After repetitive loading, the sample retained 1 mm of strain value, which indicates plastic deformation at that particular stage. The same behavior has been repeated (with different strain retention values) at varying loads. It is believed that only plastic deformation is needed for palliative treatment of oesophageal cancer patients. In a tubular configuration, the stent with rotating squares geometry was observed to have

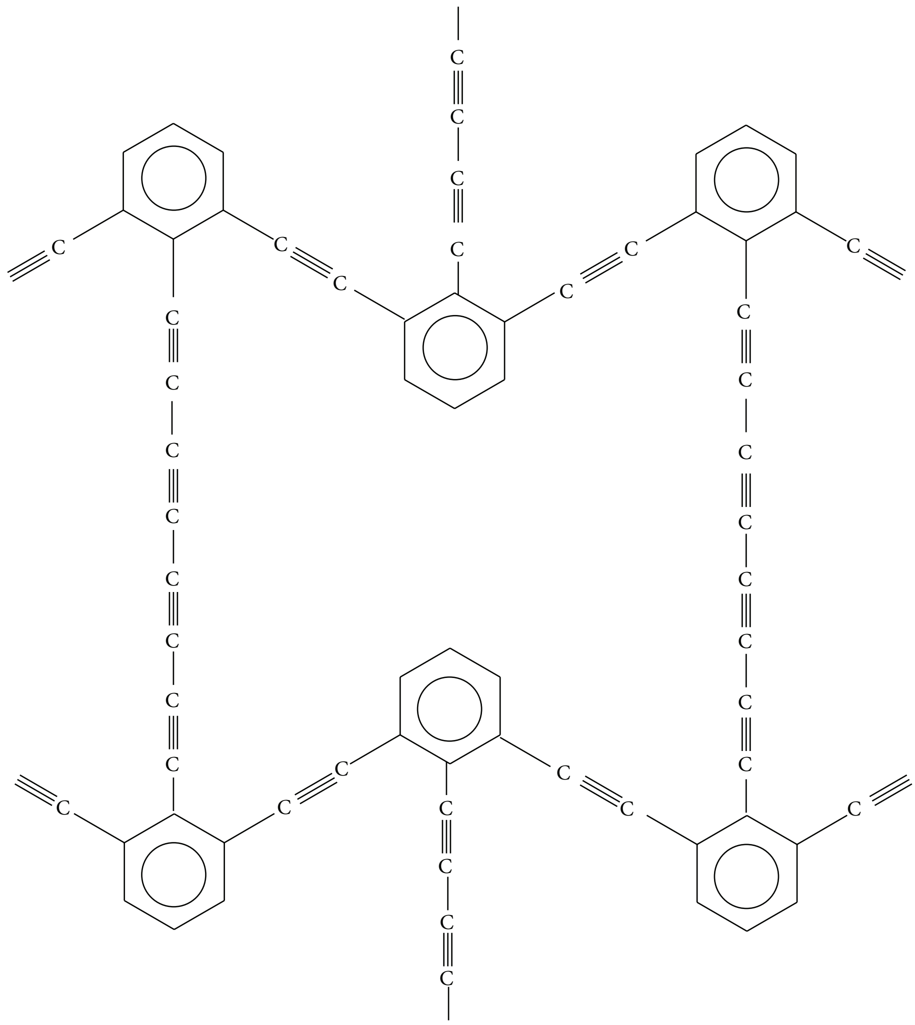


Figure 16: Unit-cell of a theoretical auxetic molecular network [2, 3].

properties that would be suitable for clinical applications such as oesophageal stenting for cancer patients (in Figure 4) [23].

As it was reported earlier that the rotating-square geometry may exhibit auxetic behaviour through rotation of the rigid squares relative to each other, it was recently established that the auxeticity can also be achieved even if the squares are not completely rigid. In this case, Poisson's ratio was reported to be dependent on the extent of deformation of the squares along with the amount of rotation of the squares. Therefore, in this study a combined model was considered which deforms through simultaneous stretching and rotation of the squares. It was found that the mechanical properties of the combined model were dependent on the respective contribution of the individual mechanisms. Also by modifying the relative magnitude of the force constants, the geometry describing the system, and the contribution of each of the two mechanisms, Poisson's ratio can be adjusted to the prescribed values [24].

Polyhedral Auxetic Nanostructures. An important class of polyhedral framework nanostructures is zeolites which are commonly used as molecular sieves because of their availability and their well-defined molecular-sized cavities and pathways. Several idealized zeolitic cage structures are theoretically predicted which possess negative ν. In most of these idealized molecular structures, the auxetic behaviour can be explained through a combination of the framework geometry and simple deformation mechanisms acting within the framework (in Figure 16) [25].

1.4.4. Auxetic Composites. Composites also demonstrate negative ν [26], especially laminated fibre reinforced composites also show negative ν, and the phenomenon is observed by controlling buckling by tailoring laminates with in-plane restrained unloaded edges where Poisson's effect was predominant to the extent that caused premature instability and significant departure from classical behaviour. Composites prepared by laminating unidirectional prepeg tapes of epoxy resin reinforced, with continuous carbon fibres, were also shown to be auxetic for θ in the range between 15 and 30°, which was in accordance with the standard laminate theory. In angle-ply composites made up of unidirectional layers of glass or high modulus carbon fibres within an epoxy resin matrix, arranged such that there are an equal number of layers

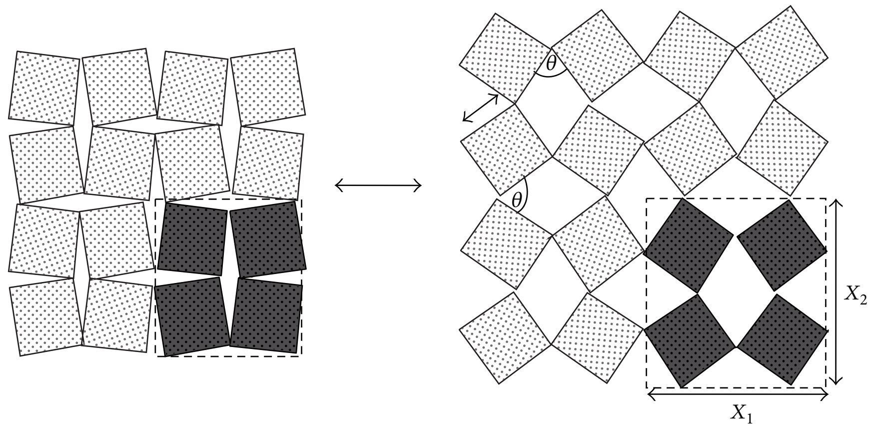


Figure 17: The geometry of the auxetic "rotating squares" structure [9].

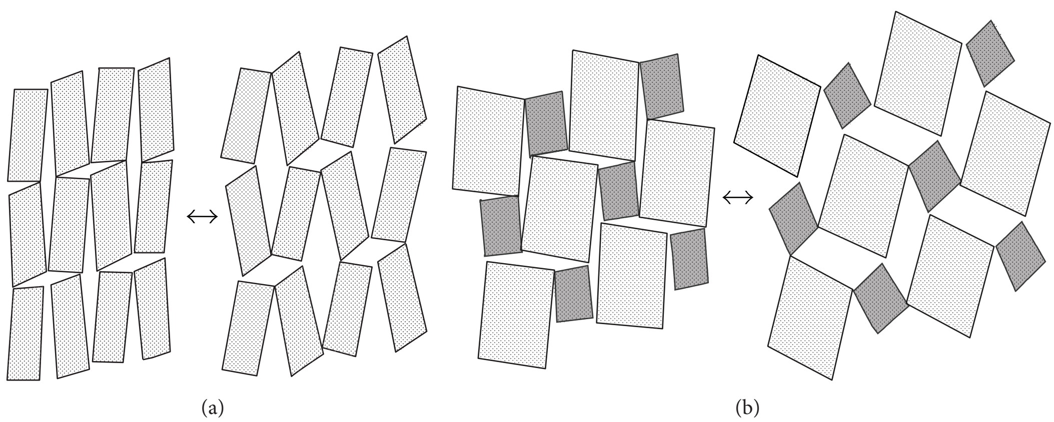


Figure 18: (a) A rotating parallelogram structure and (b) a rotating square structure built from different sized squares [9].

at an angle to a reference direction, theoretical and experimental investigations showed a large, positive in-plane Poisson's ratio and a large negative out-of-plane Poisson's ratio restricted to a single sample direction. Using the specific values of independent elastic constants in each lamina due to the extension-shear coupling, randomly oriented quasi-isotropic composite laminates were predicted to exhibit negative in-plane Poisson's ratio by random statistical analysis [8].

1.5. Modelling of Auxetic Structures. The plastic failure of a 3D auxetic strut lattice was investigated by [27], under uniaxial and transverse loads to support an ongoing research work in miniaturized strut-based sandwich cores. The beams in Figure 19 were made up of struts whose curvatures gradually decrease from zero. The plastic failure strength of an auxetic strut core under uniaxial and shear loads has been determined theoretically by the help of two parameters, that is, packing parameter P_r and relative density. The main features of the FEA models were spatial discretization of struts with single three-noded quadratic beam element, degrees of freedom were constrained at the vertices to avoid rigid body rotation of the strut, and an elastorigid plastic constitutive model represented the beam material.

The conclusions were made by comparing the theoretical data with numerical data obtained from finite element analysis using ABAQUS/standard and depicted negative Poisson's ratio effect with lateral contractions and expansions under compressive and tension for the auxetic cells [27] as shown in Figure 20.

Finite element simulations were used in another study carried out by [30], in which the results accomplished a high sensitivity of the mechanical properties for particular ranges of the auxetic geometric cell parameters. Mechanical property values were acquired by finite element simulations of plain stress uniaxial tests of auxetic honeycomb models. As it was established earlier that regular honeycombs have isotropic properties, but the unit cells of the cellular structures having a different geometric layout from the regular honeycomb unit cell are anisotropic, in general, the honeycomb unit cells are characterised by cell walls of lengths h and l, with thickness t and internal cell angle θ, and in relation to cellular material theory (CMT) their mechanical properties can be determined by Young's modulus E_c of the core material, Poisson's ratio of the core material, the cell aspect ratio α, the relative density β, and the internal cell angle (in Figure 21).

Honeycombs which exhibit negative Poisson's ratio have reentrant unit cells (in Figure 22). It was obvious that the

Figure 19: Packing parameters P_r were used to quantify the negative strut curvature [27].

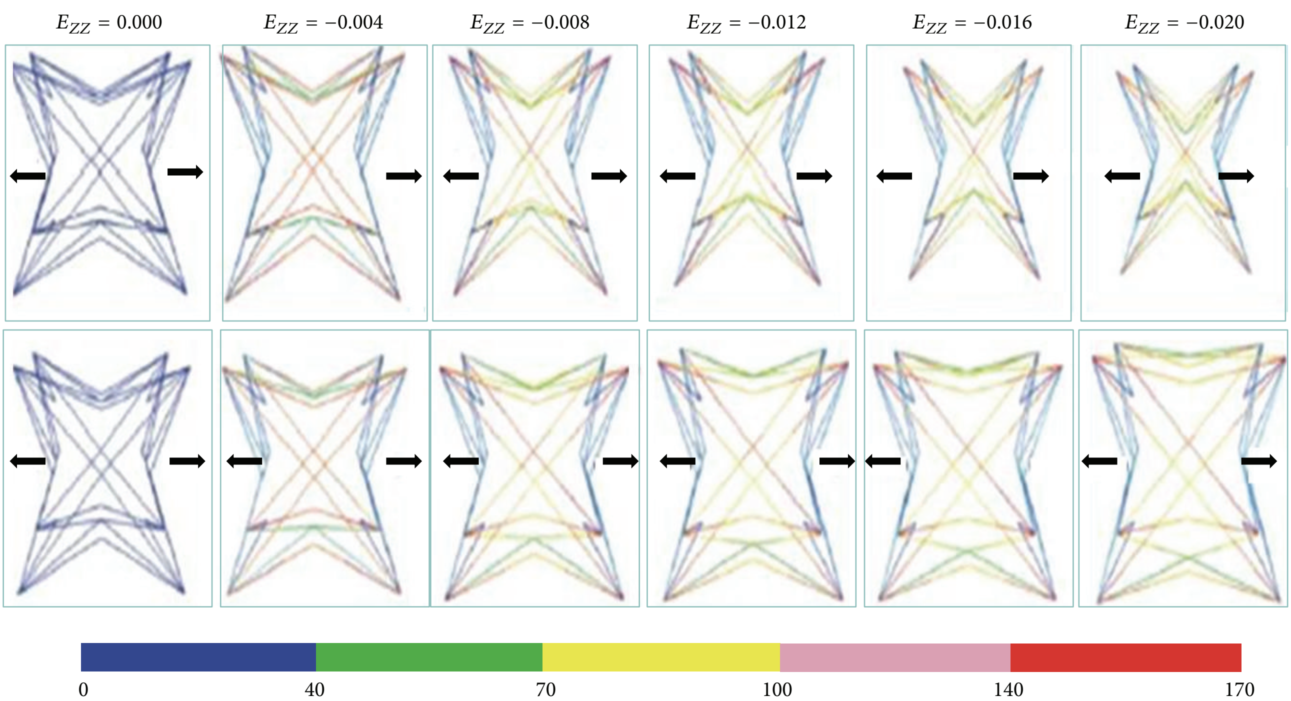


Figure 20: The colours shown are Mises stress contour plots and each column shows different configurations at the compressive strains E_{ZZ} [27].

convolutedness of this unit cells layout caused a transverse expansion of the honeycomb when pulled in the perpendicular direction. The cells convoluted because the internal cell angle was negative [30].

To evaluate the in-plane properties of reentrant cell honeycombs finite element method models were set up. The models were composed of 2508 two-node beam elements having a total of 2131 nodes. The displacements were applied to the nodes and the reaction forces were calculated on these nodes and divided by the initial area to determine the average normal stresses. For the correct plain stress loading condition, the rotations in the X_1X_2 plane of the applied displacement nodes were constrained. The geometric cell parameters played an important role in calculating the in-plane Poisson's ratio values, like an increase in the cell aspect ratio of the walls determined the rise in the maximum internal cell angle and the decrease in the magnitude of the in-plane Poisson's ratio [30].

A unique molecular network structure which was a combination of acetylene bonds and benzene rings with unusual property of a negative Poisson's ratio was modelled by [31]. This hexagonal network structure was named as (n, m)-flexin, where n is the number of acetylene links on the diagonal branches and m is the number of links on the

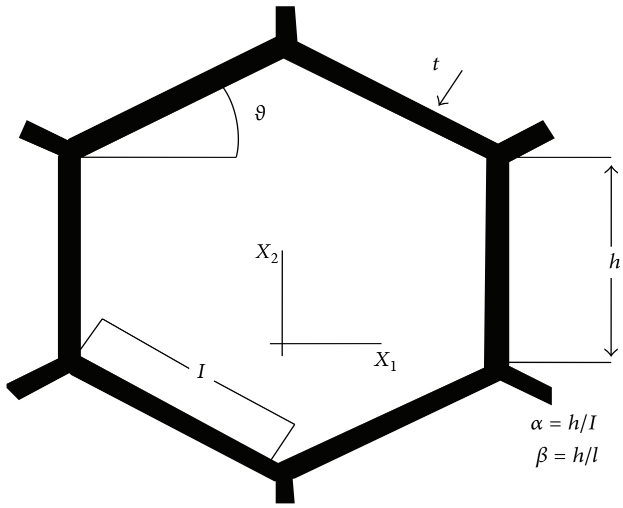


Figure 21: Unit cell of the honeycomb with characteristic dimensions [30].

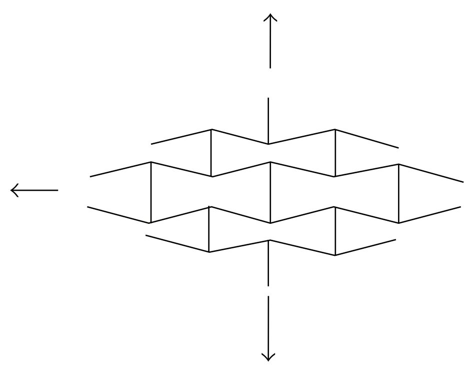


Figure 22: Honeycomb with reentrant cell units [30].

vertical branches (in Figure 23). The values of n and m can be altered to get different structural arrangements that can be either isotropic or anisotropic.

The aim of finite element modelling was to replace complex molecular structures by simpler subunits to simplify calculations, and for that purpose different finite element models were used to investigate which ones gave results closest to those from the molecular model in order to identify the most accurate subunit. The two-dimensional representations of the different finite element models for the flexin structure were shown in Figure 24 and for the reflexin structure in Figure 25. A number of models were used in these figures and were classified in cases starting from case 1 to case 6 [31].

In case 1 along the free edges the moving constraint boundary condition was used to simulate the same effect of the periodic boundary condition in the molecular model and both two- and three-dimensional beam elements were incorporated in this model. As the y-axis was an axis of symmetry and x-axis was not, therefore ideal situation was for the axes to be along the middle of the structure, which lead to case 2 which was one-quarter of the structural arrangement for case 1. A network of beam elements was used in case 3 with a matrix consisting of quadrilateral elements having Young's modulus close to zero, and across each quadratic element a separate beam element was used. Similarly, case 4 was made except that the beam was made up of quadrilateral elements in case 3. Case 5 was used by having two-dimensional beam elements which was similar to case 3 but without the presence of matrix. In case 6 three-dimensional beam elements were used [31].

The two-dimensional beam elements were used to model a rectangular cross-section with unit depth, while the three-dimensional beam was used to model a circular cross-section resulting from C–C and C≡C links. Moving boundary constraints along the free edges and roller-bearing boundary conditions along the x- and y-axes were used to give transverse contraction or expansion under loading. In either the x- or y-direction, pressure loading was applied to one of the two free edges [31].

Auxetic Design through Topology Optimization. A mathematical technique known as topology optimization has been used to design structures that can meet specific requirements. A 2-dimensional metallic sheet that has low porosity has been designed and it has been demonstrated that Poisson's ratio

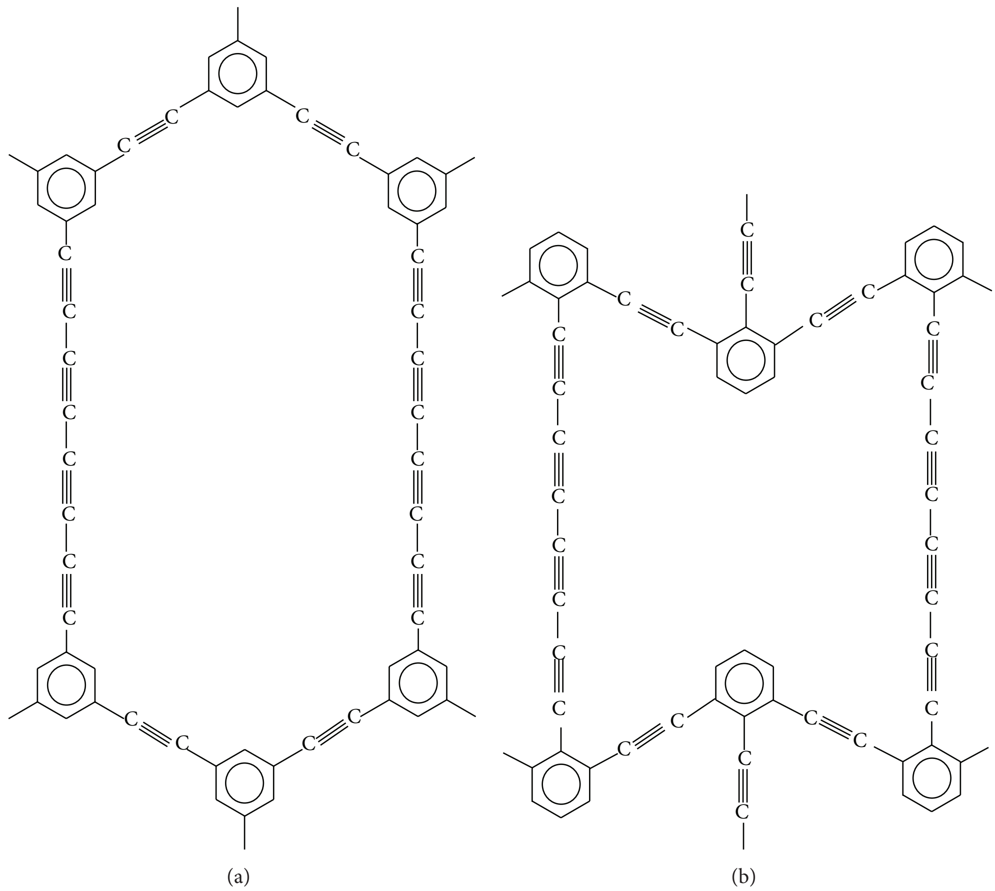


Figure 23: Different Poisson's ratios of molecular networks, (a) (1,4)-flexin with a positive Poisson's ratio; (b) (1,4)-reflexin with a negative Poisson's ratio [31].

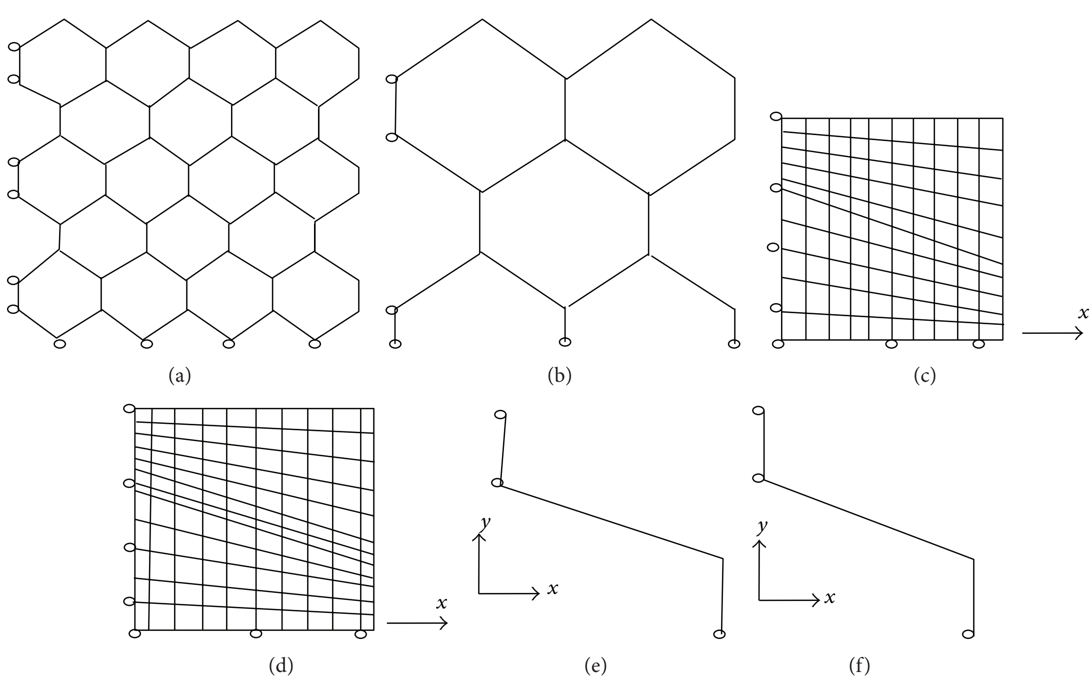


Figure 24: 2D representations of various FEM models of flexin structure; (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) case 5, and (f) case 6 [31].

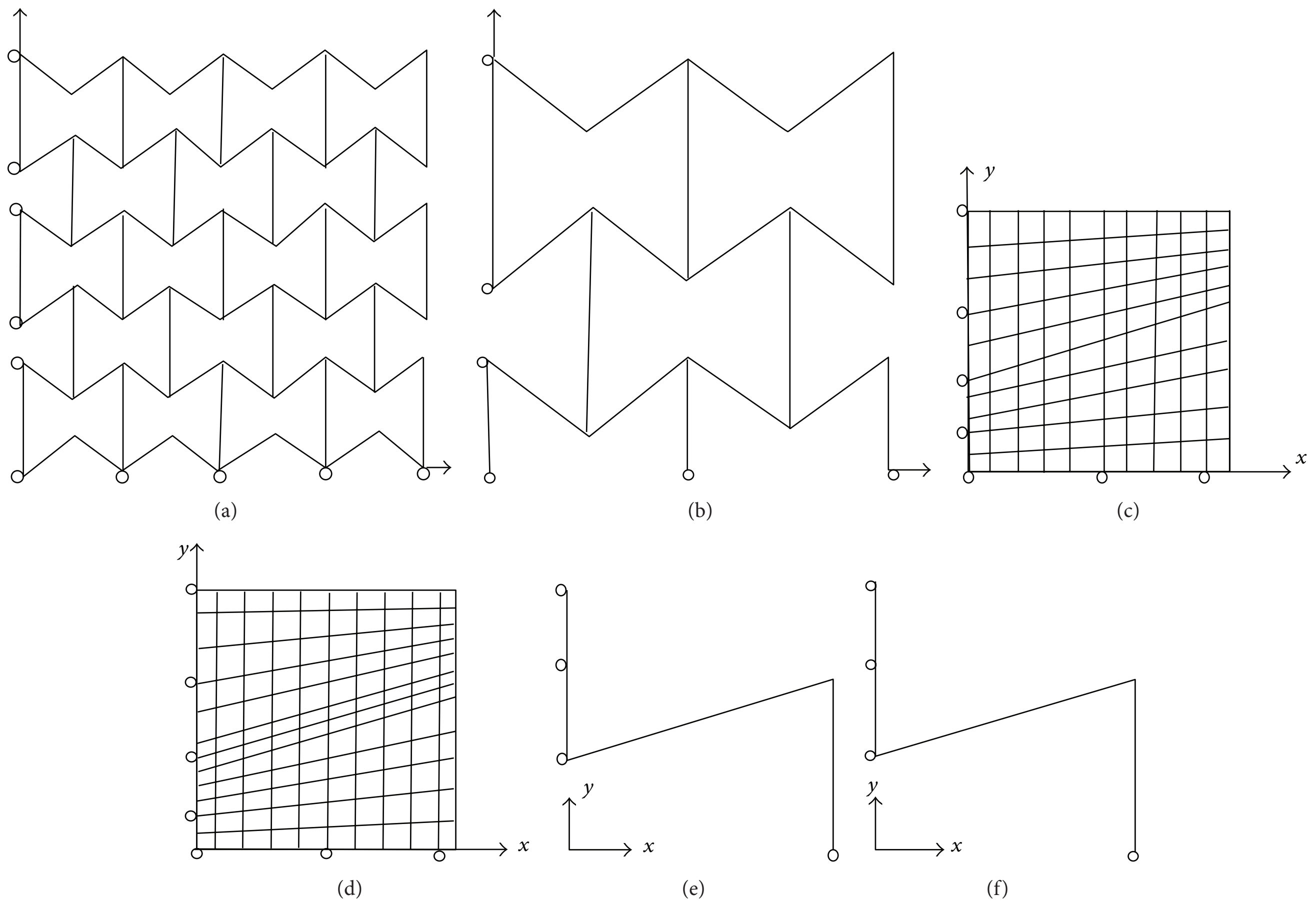


Figure 25: 2D representations of various FEM models for reflexin structure, (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) case 5, and (f) case 6 [31].

may be manipulated by a change in the aspect ratio of the voids. Poisson's ratio is found to decrease with increasing aspect ratios. Adjusting even one of the parameters in the structure can cause large negative Poisson's ratio values [4].

In another study by [32] topology optimization has been modified to a mixed-integer linear programming problem. In this approach, the optimal designs have no hinge regions, as stress constraints have been thoroughly addressed. Fabrication tests have shown that auxetic planar structures may be successfully obtained using this approach.

The technique of topology optimization has been used for designing microstructural auxetics. This technique takes into account nonconvexity issues. Mesh refining leads to richer and better microstructures [33].

Conflict of Interests

It is hereby declared that there is no conflict of interests.

References

[1] B. Ellul, M. Muscat, and J. N. Grima, "On the effect of the Poisson's ratio (positive and negative) on the stability of pressure vessel heads," *Physica Status Solidi B: Basic Research*, vol. 246, no. 9, pp. 2025–2032, 2009.

[2] K. E. Evans and A. Alderson, "Auxetic materials: functional materials and structures from lateral thinking!," *Advanced Materials*, vol. 12, no. 9, pp. 617–628, 2000.

[3] K. E. Evans and K. L. Alderson, "Auxetic materials: the positive side of being negative," *Engineering Science and Education Journal*, vol. 9, no. 4, pp. 148–154, 2000.

[4] M. Taylor, L. Francesconi, M. Gerendás, A. Shanian, C. Carson, and K. Bertoldi, "Low porosity metallic periodic structures with negative poisson's ratio," *Advanced Materials*, vol. 26, no. 15, pp. 2365–2370, 2014.

[5] H. Wan, H. Ohtaki, S. Kotosaka, and G. Hu, "A study of negative Poisson's ratios in auxetic honeycombs based on a large deflection model," *European Journal of Mechanics, A/Solids*, vol. 23, no. 1, pp. 95–106, 2004.

[6] N. Gaspar, C. W. Smith, E. A. Miller, G. T. Seidler, and K. E. Evans, "Quantitative analysis of the microscale of auxetic foams," *Physica Status Solidi (B) Basic Research*, vol. 242, no. 3, pp. 550–560, 2005.

[7] J. N. Grima, R. Gatt, A. Alderson, and K. E. Evans, "On the potential of connected stars as auxetic systems," *Molecular Simulation*, vol. 31, no. 13, pp. 925–935, 2005.

[8] W. Yang, Z.-M. Li, W. Shi, B.-H. Xie, and M.-B. Yang, "On auxetic materials," *Journal of Materials Science*, vol. 39, no. 10, pp. 3269–3279, 2004.

[9] J. N. Grima and K. E. Evans, “Auxetic behavior from rotating squares,” *Journal of Materials Science Letters*, vol. 19, no. 17, pp. 1563–1565, 2000.

[10] K. L. Alderson, R. S. Webber, and K. E. Evans, “Novel variations in the microstructure of auxetic ultra-high molecular weight polyethylene. Part 2: mechanical properties,” *Polymer Engineering and Science*, vol. 40, no. 8, pp. 1906–1914, 2000.

[11] G. E. Stavroulakis, “Auxetic behaviour: appearance and engineering applications,” *Physica Status Solidi (B) Basic Research*, vol. 242, no. 3, pp. 710–720, 2005.

[12] L. White, “Auxetic foam set for use in smart filters and wound dressings,” *Urethanes Technology International*, vol. 26, no. 4, pp. 34–36, 2009.

[13] A. Alderson, J. Rasburn, K. E. Evans, and J. N. Grima, “Auxetic polymeric filters display enhanced de-fouling and pressure-compensation properties,” *Membrane Technology*, no. 137, pp. 6–8, 2001.

[14] M. Bianchi, F. L. Scarpa, and C. W. Smith, “Stiffness and energy dissipation in polyurethane auxetic foams,” *Journal of Materials Science*, vol. 43, no. 17, pp. 5851–5860, 2008.

[15] F. Scarpa, J. Giacomin, Y. Zhang, and P. Pastorino, “Mechanical performance of auxetic polyurethane foam for antivibration glove applications,” *Cellular Polymers*, vol. 24, no. 5, pp. 253–268, 2005.

[16] C. W. Smith, J. N. Grima, and K. E. Evans, “Novel mechanism for generating auxetic behaviour in reticulated foams: missing rib foam model,” *Acta Materialia*, vol. 48, no. 17, pp. 4349–4356, 2000.

[17] Y. Prawoto, “Seeing auxetic materials from the mechanics point of view: a structural review on the negative Poisson’s ratio,” *Computational Materials Science*, vol. 58, pp. 140–153, 2012.

[18] N. Chan and K. E. Evans, “Fabrication methods for auxetic foams,” *Journal of Materials Science*, vol. 32, no. 22, pp. 5945–5953, 1997.

[19] N. Chan and K. E. Evans, “Microscopic examination of the microstructure and deformation of conventional and auxetic foams,” *Journal of Materials Science*, vol. 32, no. 21, pp. 5725–5736, 1997.

[20] N. Ravirala, A. Alderson, K. L. Alderson, and P. J. Davies, “Auxetic polypropylene films,” *Polymer Engineering and Science*, vol. 45, no. 4, pp. 517–528, 2005.

[21] P. J. Mcmullan, S. Kumar, and A. C. Griffin, “Textile fibres engineered from molecular auxetic polymers,” National Textile Center Annual Report (n.d.), 2007.

[22] W. Ren, P. J. McMullan, and A. C. Griffin, “Stress-strain behavior in main chain liquid crystalline elastomers: effect of crosslinking density and transverse rod incorporation on ‘Poisson’s ratio’,” *Physica Status Solidi B: Basic Research*, vol. 246, no. 9, pp. 2124–2130, 2009.

[23] M. N. Ali and I. U. Rehman, “An Auxetic structure configured as oesophageal stent with potential to be used for palliative treatment of oesophageal cancer; development and in vitro mechanical analysis,” *Journal of Materials Science: Materials in Medicine*, vol. 22, no. 11, pp. 2573–2581, 2011.

[24] D. Attard, E. Manicaro, R. Gatt, and J. N. Grima, “On the properties of auxetic rotating stretching squares,” *Physica Status Solidi B: Basic Research*, vol. 246, no. 9, pp. 2045–2054, 2009.

[25] J. N. Grima, R. Jackson, A. Alderson, and K. E. Evans, “Do zeolites have negative Poisson’s ratios?” *Advanced Materials*, vol. 12, no. 24, pp. 1912–1918, 2000.

[26] S. Donescu, V. Chiroiu, and L. Munteanu, “On the Young’s modulus of a auxetic composite structure,” *Mechanics Research Communications*, vol. 36, no. 3, pp. 294–301, 2009.

[27] M. Doyoyo and J. Wan Hu, “Plastic failure analysis of an auxetic foam or inverted strut lattice under longitudinal and shear loads,” *Journal of the Mechanics and Physics of Solids*, vol. 54, no. 7, pp. 1479–1492, 2006.

[28] U. O. Malta, “Maltese scientists.work on front cover of leading international scientific journal,” 2010, http://home.um.edu.mt/auxetic/press/.

[29] J. N. Grima, E. Manicaro, and D. Attard, “Auxetic behaviour from connected different-sized squares and rectangles,” *Proceedings of The Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 467, no. 2126, pp. 439–458, 2011.

[30] F. Scarpa, P. Panayiotou, and G. Tomlinson, “Numerical and experimental uniaxial loading on in-plane auxetic honeycombs,” *Journal of Strain Analysis for Engineering Design*, vol. 35, no. 5, pp. 383–388, 2000.

[31] M. A. Nkansah, K. E. Evans, and I. J. Hutchinson, “Modeling the mechanical-properties of an auxetic molecular network,” *Modelling and Simulation in Materials Science and Engineering*, vol. 2, no. 3, pp. 337–352, 1994.

[32] R. Kureta and Y. Kanno, “A mixed integer programming approach to designing periodic frame structures with negative Poisson’s ratio,” *Optimization and Engineering*, vol. 15, no. 3, pp. 773–800, 2014.

[33] N. T. Kaminakis and G. E. Stavroulakis, “Design of auxetic microstructures using topology optimization,” *Structural Longevity*, vol. 8, no. 1, pp. 1–6, 2012.