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**Abstract:** The current status of research into auxetic (negative Poisson's ratio) materials is reviewed, with particular focus on those aspects of relevance to aerospace engineering. Developments in the modelling, design, manufacturing, testing, and potential applications of auxetic cellular solids, polymers, composites, and sensor/actuator devices are presented. Auxetic cellular solids in the forms of honeycombs and foams are reviewed in terms of their potential in a diverse range of applications, including as core materials in curved sandwich panel composite components, radome applications, directional pass band filters, adaptive and deployable structures, MEMS devices, filters and sieves, seat cushion material, energy absorption components, viscoelastic damping materials, and fastening devices. The review of auxetic polymers includes the fabrication and characterization of microporous polymer solid rods, fibres, and films, as well as progress towards the first synthetic molecular-level auxetic polymer. Potential auxetic polymer applications include self-locking reinforcing fibres in composites, controlled release media, and self-healing films. Auxetic composite laminates and composites containing auxetic constituents are reviewed and enhancements in fracture toughness, and static and low velocity impact performance are presented to demonstrate potential in energy absorber components. Finally, the potential of auxetics as strain amplifiers, piezoelectric devices, and structural health monitoring components is presented.

**Keywords:** auxetic, negative Poisson's ratio, smart materials and systems, composites, honeycombs, foams, polymeric fibres and films

## 1 INTRODUCTION

Over the past three decades, developments in structural engineering design and technology in the aircraft industry as well as in the automotive, sports, and leisure sectors have demanded the development of new, high performance materials to meet higher engineering specifications. The general requirements of such materials are to provide a combination of high stiffness and strength with significant weight savings, resistance to corrosion, chemical resistance, low maintenance, and reduced costs.

This has resulted in a drive towards increased usage of composite materials in aerospace applications. For example, both Boeing and Airbus are making extensive usage levels on the B787 and A380, respectively, with up to 50 per cent by weight of the airframe for the B787 being plastic [**1**]. The main driver for this is the reduced weight, leading to reduced fuel costs, emissions, and maintenance. A stark illustration of this can be seen when American C-17 Globemaster transports are considered. Since 1999, all C-17s have had composite tails, each requiring 2000 fewer parts, 42 000 fewer fasteners, and weighing 213 kg less than their aluminium predecessors [**2**].

Extensive use of composites has also penetrated the development of maritime and battlefield helicopters and unmanned aerial vehicles (UAVs). UAVs are no longer simple and inexpensive, but are produced from a range of specialized materials primarily to increase flight time [**3**]. These include high molecular weight polyethylene, quartz, glass, aramid, and carbon fibres with a variety of resins. Specific advantages

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in the use of these materials are the ability to tailor properties by orientation of the reinforcing fibres in the direction of maximum stiffness and strength, the ability to fabricate intricate parts, and low radar and microwave absorption, which provides stealth capabilities by making radar detection difficult.

However, composite materials in particular do show certain disadvantages. Among the key properties sought by engineers in designing advanced aerospace structures are high shear strength and modulus, high impact strength particularly in relation to low velocity impacts resulting from runway debris or bird strikes, increased energy absorption, improved fatigue resistance, and easy detection and repair of damaged sections. This combination of properties is not found in today's composite materials, which are poor especially in relation to repair, impact damage, and energy absorption.

One new class of materials which could provide further advantages over the materials currently deployed is auxetic materials [**4**]. These materials have a negative Poisson's ratio, $\nu$, which means that they expand in the lateral direction when stretched longitudinally i.e. in simple terms, they get fatter when pulled. This is a novel interesting effect in itself but it is the consequence of having a negative $\nu$ that marks these materials as being candidate aerospace solutions for the future.

From classical elasticity theory, many properties depend on the Poisson's ratio of the material. A simple and well known example of this is the shear modulus, $G$, where

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

and $E$ is the Young's modulus. It can clearly be seen that as $\nu$ approaches $-1$, which is the limit for an isotropic material, the shear modulus will become infinitely large. Other properties to show this tendency to approach infinite extremes as $\nu \to -1$ include indentation resistance, thermal shock resistance, and fracture toughness, all of which have been evaluated and have shown enhancements. This will be discussed in some detail below. Thus, auxetic materials show certain enhanced properties because of their negative Poisson's ratio.

The physical effect of a negative $\nu$ can also be exploited for a variety of applications. One such application is illustrated in Fig. 1. When a conventional material is subjected to an out-of-plane bending moment, for example, to form a wing panel or nose cone, it displays anticlastic curvature, showing a distinctive saddle shape. An auxetic material, however, will display synclastic or double curvature, resulting in a dome shape without the need for excessive machining or forcing the material to take up the desired shape, resulting in possible damage [**5**].

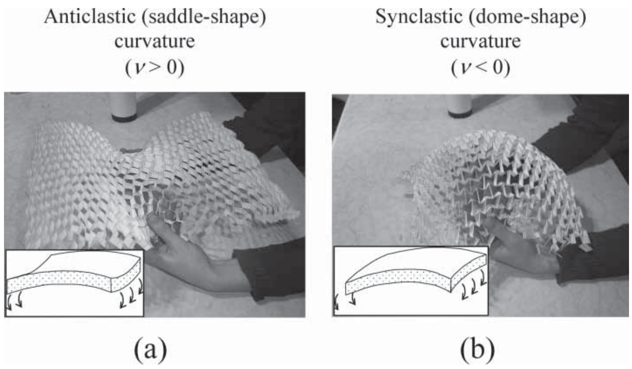


**Fig. 1** (a) Anticlastic (saddle-shape) curvature of a positive Poisson's ratio material and (b) synclastic (dome-shape) curvature of a negative Poisson's ratio (auxetic) material undergoing out-of-plane bending (schematic inserts adapted from [**5**])

Auxetic materials are still an emerging class of materials. It should be noted that natural auxetic materials do exist, for example, single crystals of arsenic [**6**] and cadmium [**7**], $\alpha$-cristobalite [**8**], iron pyrites [**9**], and many cubic elemental metals [**10**]. In addition, biological materials have also been found to be auxetic and these include certain forms of skin (e.g. cat skin [**11**], salamander skin [**12**], and cow teat skin [**13**]) and load-bearing cancellous bone from human shins [**14**]. However, research into auxetics began in earnest in the late 1980s with the fabrication of an auxetic polyurethane foam [**15**]. Since then, a wide range of materials have been produced covering the major classes of materials (polymers, composites, metals, and ceramics).

This review of auxetic materials has been structured by (but is not limited to) consideration of a typical component used in aerospace applications – the sandwich panel composite. A typical sandwich panel composite section is shown in Fig. 2. The component comprises top and bottom outer skin layers bonded to an internal core material by adhesive interface layers. The outer skins are typically made out of aluminium or fibre-reinforced composite laminate material and provide in-plane strength and stiffness as well as protection to the internal materials. The core material provides out-of-plane strength and stiffness for low weight. The core material is typically a foam or a honeycomb and can be a metal, polymer, fibre-reinforced polymer, or phenolic resin-coated aramid paper. Additional constituents may be incorporated to, for example, impart sensor and actuator functionality for structural health monitoring capabilities. The component may be required to be curved to form, for example, the doubly curved nose cone component.

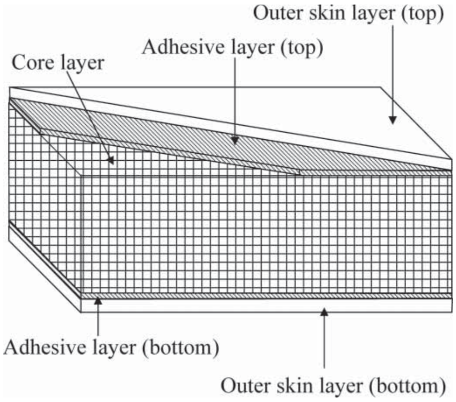


**Fig. 2** Sandwich panel construction

The fabrication, characterization, testing, and possible applications, particularly in the aerospace industry, for auxetic cellular solids (foams and honeycombs), polymers, and composite materials are, therefore, considered in more detail below, along with an indication of the potential in sensor and actuator devices.

## 2 CELLULAR SOLIDS

The development of auxetic cellular solids has focused mainly on two main classes of materials: honeycombs and foams.

### 2.1 Honeycombs

The earliest example of an auxetic honeycomb is the tessellating re-entrant hexagon topology shown schematically in Fig. 3 and developed during the 1980s [**16–19**]. For ease of demonstration, Fig. 3 shows the honeycomb deforming by hinging of the diagonal ribs in response to an applied uniaxial load. Alignment of the diagonal ribs along the horizontal direction of applied stretch causes the ribs aligned along the vertical direction to move apart, thereby imparting the auxetic effect. In reality, most honeycombs of this type deform predominantly by flexure of the diagonal ribs, with hinging and axial stretching of the ribs also occurring simultaneously [**16, 20, 21**]. Flexure of the ribs also leads to auxetic behaviour in the re-entrant hexagonal honeycomb system.

There is clear potential for auxetic honeycomb as the core material in a curved body part for aerospace (such as a nose cone). Not only does the auxetic honeycomb naturally adopt a doubly curved shape without the need for machining or forcing into shape, as mentioned above, but also the out-of-plane strength and stiffness of the core material is maximized in the auxetic case as a consequence of the ribs always being aligned normal to the curved surface. This is not the case for a curved core material made from machining of a thick monolithic honeycomb, for example. A prototype curved sandwich panel comprising an auxetic re-entrant honeycomb core sandwiched between two outer laminate skins has been successfully produced [**22**].

Curved honeycomb core material is also required in microwave absorber applications such as radome shells, where the requirement of the core material is to provide a low dielectric property structure with which to absorb microwave radiation. Auxetic re-entrant honeycombs have been shown to lead to optimal combined mechanical and dielectric properties for radome applications [**23**]. More recently, further studies into optimizing the wave propagation characteristics (frequency band and low frequency directionality) of honeycomb systems have shown promise for auxetic re-entrant honeycombs as directional pass band mechanical filters [**24**].

One disadvantage of the re-entrant honeycomb system is the difficulty in manufacturing the honeycomb on a commercial scale. The usual method of gluing strips of material together at regular intervals and then pulling to produce the conventional hexagonal honeycomb geometry cannot be employed for the re-entrant honeycomb geometry. Other methods are possible (such as rapid prototyping and moulding techniques), but clearly these will require justification through a full cost-benefit analysis before current methods of honeycomb manufacture for commercial aerospace use are abandoned.

Alternatively, other topologies leading to the auxetic effect in honeycomb systems might eventually yield a commercially acceptable auxetic core in terms of both manufacturability and performance. Figure 4 shows some alternative honeycomb topologies to the tessellating re-entrant hexagon motif which give rise to auxetic behaviour. The chiral honeycomb [**25**] (Fig. 4(a)) achieves the auxetic effect through wrapping or unwrapping of the ligaments around the circular cross-section nodes in response to an applied force. Rib flexure and/or hinging in the star honeycomb [**26**] (Fig. 4(b)) and double arrow-head honeycomb [**27**]

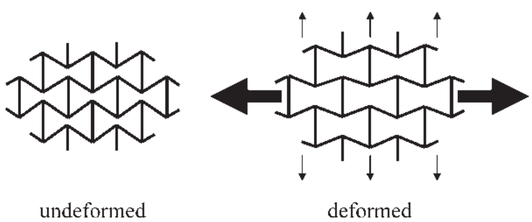


**Fig. 3** Re-entrant honeycomb [**16–19**] in the undeformed and deformed (via hinging of ribs in response to applied horizontal stretching) states

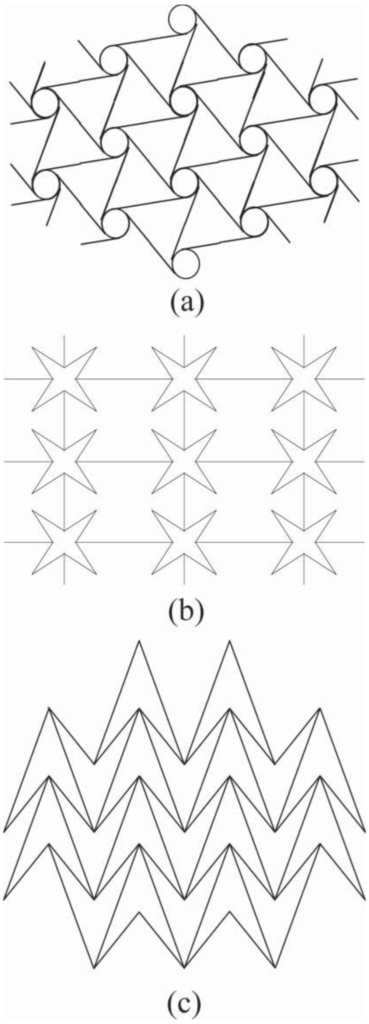



**Fig. 4** Auxetic honeycomb topologies: (a) chiral [**25**]; (b) star [**26**]; (c) double arrowhead [**27**]

(Fig. 4(c)) leads to opening or closing of the stars and arrowheads, respectively, to give auxetic behaviour.

In addition to the benefits associated with the auxetic property, the chiral honeycomb has potential due to the particular structural features inherent in the geometry. The cylinders have been shown to lead to improved out-of-plane compressive strength under flatwise loading [**28**, **29**], while the ligaments provide resistance to out-of-plane shear loading [**30**], which is important in relation to the flexural stiffness of sandwich panels. The ability to decouple the out-of-plane compressive strength and shear modulus in terms of the cylinders and ligaments, respectively, allied to the auxetic property leads to the potential to optimally tailor the mechanical response and shape of the honeycomb, making chiral honeycombs potentially especially attractive core materials for sandwich panel components.

Combining the auxetic effect due to structural geometry with additional functionality derived in some manner from the rib material itself opens up the potential for further applications. Chiral and hexagonal honeycombs made from shape memory alloy ribbon material show the potential for thermally activated adaptive and deployable structures [**31**, **32**]. Recent work has started to develop the concept of employing chiral honeycombs in truss-core assemblies for adaptive lifting devices such as aircraft wings and helicopter rotor blades [**33**, **34**]. The use of microfabrication techniques has been demonstrated to lead to potential for auxetic honeycombs in applications as diverse as MEMS devices such as microgrippers and micropositioners [**27**, **35**].

Smart applications can, however, be developed solely on the auxetic property itself, without necessarily requiring additional (multi)functionality. An example here is the self-regulating honeycomb filter or sieve which utilizes the double curvature bending mode characteristic of an auxetic material to compensate for pressure build-up due to fouling of the filter [**36–38**]. As a conventional filter becomes fouled, the effective porosity of the filter and, therefore, the filtration efficiency decrease. For an auxetic honeycomb filter, the increased pressure on the filter due to fouling causes double curvature of the honeycomb which in turn increases the porosity of the filter to compensate for the reduced porosity from fouling. The smart auxetic filter therefore detects a decrease in porosity due to fouling and acts to increase the porosity to maintain filtration efficiency. Alternatively, a cleanable filter capability exists as a consequence of the high volume change nature of the auxetic effect. By applying an in-plane tension to the auxetic honeycomb filter the porosity is increased, thus enabling release of particulates blocking the pores of the filter.

### 2.2 Foams

A method of converting fully reticulated open-cell thermoplastic (polyurethane) foam displaying positive Poisson's ratio behaviour into auxetic form was reported in 1987 [**15**], and subsequently methods for the production of thermoplastic (silicone rubber) and metallic (copper) auxetic foam have been developed [**15**, **39**]. Foam slabs having dimensions of the order of a few 10s of centimetres have been successfully produced [**40**, **41**]. Foams displaying isotropic and anisotropic mechanical properties can be produced [**41**, **42**]. Microcellular foam and closed-cell foam have also both been converted into auxetic form [**43**, **44**].

Figure 5 shows micrographs of a polyurethane foam before and after conversion to auxetic form, showing a contorted three-dimensional re-entrant topology

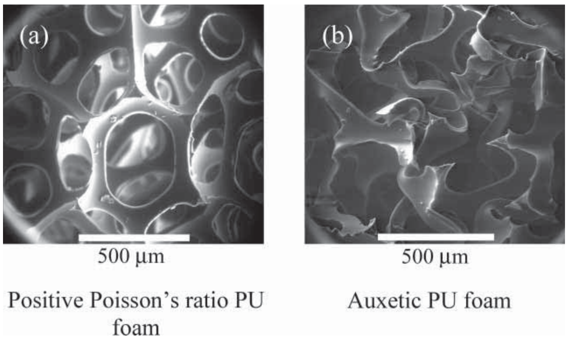


**Fig. 5** PU foams: (a) unconverted (positive Poisson's ratio) foam; (b) converted (auxetic) foam [**45**]

for the auxetic foam compared to the regular convex cell structure of the conventional starting foam material [**45**].

Auxetic foam displays synclastic curvature [**15**], improved resilience [**15**], indentation resistance [**46, 47**], shear resistance [**48**], fracture toughness [**49**], and vibration control [**50**, **51**]. Combinations of some of these properties point to significant potential as sandwich panel component core material and as seat cushioning material [**52**] with improved comfort characteristics in aerospace and automotive applications. The studies into the dynamic behaviour of auxetic foam [**43**, **50**, **51**, **53–55**] show an increase in the loss factor and, therefore, potential in energy absorption devices and viscoelastic damping applications. Highly anisotropic auxetic foams [**42**] have potential as free-layer damping materials where a high bending stiffness and a low compressional modulus are required to produce in-plane extensional damping properties (to damp flexural waves present in the substrate) and a low through-thickness compressional wave speed.

Auxetic foam has also been used to demonstrate applications which exploit the auxetic effect directly. Studies on auxetic foam have revealed similar outcomes in terms of mass transport potential [**38**, **56**] as found for the honeycomb filters referred to above. The use of auxetic materials as fastening devices has been shown in the form of an auxetic copper foam press-fit fastener [**57**]. In this device, the copper foam contracts radially as it is pushed (compressed) into a hole, thereby easing the process of insertion of the fastener. When the copper foam is pulled (stretched) to try to extract it from the hole, the foam expands radially and locks into the walls of the surrounding hole, leading to increased pull-out resistance for the fastener.

Multi-functional auxetic foams have been developed through soaking the foams in electrorheological and magnetorheological (MR) fluids, and their mechanical, electromagnetic, and acoustic properties are investigated [**58**, **59**]. Application of magnetic or electric fields leads to changes in the stiffness of the foams, and significant magnetostrictive effects have been observed. Compared to conventional foams the MR-coated auxetic foams demonstrate increases in the loss factor and refractive index.

## 3 POLYMERS

### 3.1 Microporous polymer cylinders

The auxetic effect was first observed in microporous polymeric material in 1989 [**60**, **61**]. In this case, an expanded form of polytetrafluoroethylene (PTFE) was found to exhibit a highly anisotropic negative Poisson's ratio as low as $\nu = -12$. This is due to its complex microstructure which consists of nodules interconnected by fibrils and is shown in the micrograph of Fig. 6. In essence, the re-entrant structure of the foams and honeycombs has been reproduced by the nodule–fibril structure and the dominant deformation mechanism for auxetic behaviour is nodule translation through hinging of the fibrils [**61–63**].

The observation of the auxetic effect in PTFE revealed that there are no underlying reasons why other polymers should not be processed in such a manner as to produce this particular microstructure. A batch process consisting of three distinct stages of compaction [**64**], sintering [**65**], and extrusion [**66**] has been developed and used to produce auxetic microporous samples of ultra high molecular weight polyethylene [**67**], polypropylene (PP) [**68**], and nylon [**69**]. The role of the compaction stage is to impart structural integrity to the extrudate. If the compaction stage is omitted, the extrudate produced is highly fibrillar and very auxetic but has low mechanical properties and low density [**70**, **71**]. Equally, the extrusion stage may also be replaced by compaction followed by multiple sintering, resulting in a material which retains some of its auxeticity, but has excellent structural integrity [**72**].

Two other interesting features have been examined for these materials – the indentation resistance and the

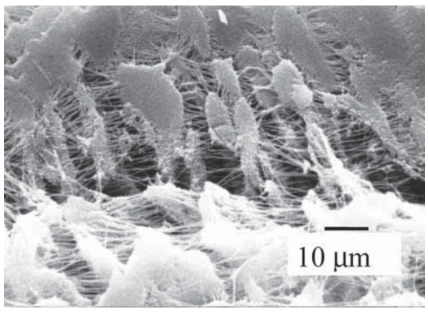


**Fig. 6** Nodule–fibril microstructure of auxetic PTFE [**59**]

absorption of ultrasound. Enhancements of up to four times over conventional materials have been found in indentation resistance for the more structurally sound auxetic polymers [**73**] whereas for ultrasound absorption, the very highly fibrillar forms of the polymers are so good at absorbing the signal that it was undetectable [**74**]. Thus, the possibility of tailoring the mechanical properties through processing is apparent for the microporous polymers.

### 3.2 Microporous polymer fibres

There is a disadvantage in using the processing route developed for auxetic polymers and this is that it is geared towards the production of cylinders. Although useful for assessing processing parameters and measuring some simple mechanical properties, this shape is difficult to machine and to use in applications-based work. Consequently, in 2001, auxetic fibres were fabricated using a partial melt spinning technique. PP [**75**], polyester [**76**], and nylon [**77**] fibres have been produced. This development has opened up areas such as reinforcements in auxetic composites, which is considered below, and technical textile applications [**78**]. An example of a potential technical textile application is the 'smart bandage' concept which releases wound healing agent in a controlled manner in response to swelling of an infected wound. The concept describes a bandage fabric consisting of auxetic fibres containing a wound healing drug within the fibre micropores [**78**]. Wound swelling due to infection stretches the fibres in the bandage and therefore causes the micropores to open up (due to the auxetic effect) to release the wound healing agent onto the wound. Once the wound healing agent has taken effect, the wound swelling decreases, causing the fibres and fibre micropores to recover their original dimensions and thus stop the controlled release of the active agent.

The processing route can also be adapted to produce auxetic PP films [**79**], which have in-plane Poisson's ratios approaching $-1$. Auxetic films are potentially important as membrane materials and preliminary experiments have been performed showing their potential as self-healing films due to the closing up of a tear when the film is placed under tension along the direction of the tear [**77**, **79**].

### 3.3 Molecular-level polymers

In order to develop polymeric fibres having high strength and stiffness properties it will be necessary to produce polymers in which the auxetic effect is derived from microstructures operating at the molecular and nano scales. As already noted, a number of inorganic and metallic materials exist where the auxetic effect occurs at the molecular scale [**6–10**, **80**]. Despite this, and the presence of a significant literature on modelling studies of auxetic molecular-level materials [**4**, **81–86**], no molecular-level auxetic polymers have so far been synthesized.

Early molecular models have used the macroscopic re-entrant honeycomb structure as a template for polymeric molecular honeycombs. Auxetic behaviour has been predicted [**4**, **85–87**] but these structures are too heavily cross-linked to be realized in practice.

The most promising route to a successful molecular-level polymer is in the form of a proposed liquid crystalline polymer (LCP) [**88**] shown in Fig. 7. The LCP consists of chains of rigid rod molecules connected by flexible spacer groups along the chain lengths. The flexible spacer groups attach to the ends of some of the rigid rods (terminally attached), and to the sides of the other rigid rods (laterally attached). In the unstressed state, all the rigid rods are proposed to be oriented along the chain directions. The proposed mechanism for auxetic behaviour is then the rotation of the laterally attached rods upon stretching of the LCP, causing an increase in the interchain separation. Progress has been made on the synthesis of these systems [**88**, **89**] and molecular modelling has been used to predict auxetic behaviour [**90**].

## 4 FIBRE-REINFORCED COMPOSITES

There are two approaches that can be used to produce auxetic laminate composites. The route closest to conventional manufacture is to use off-the-shelf pre-preg material and the conventional manufacturing techniques of vacuum bagging. In this case, the effect is produced by selecting suitable stacking sequences. Initially, modelling was carried out and this allows

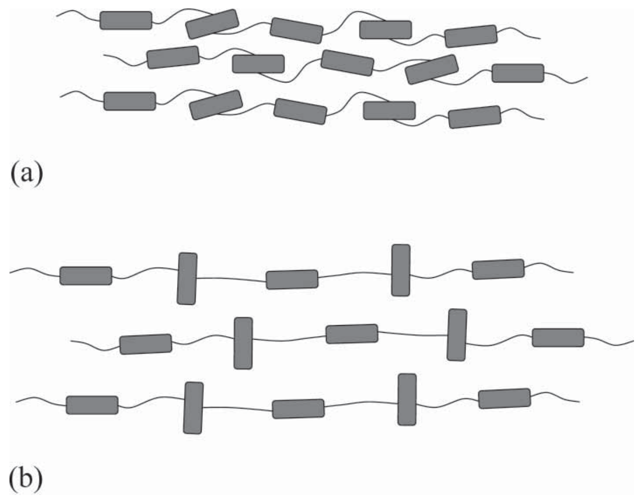


**Fig. 7** Theoretical LCP in (a) undeformed and (b) deformed state due to horizontal stretching [**87**]

sequences to be predicted that could produce a negative Poisson's ratio either in-plane or out-of-plane [**91**, **92**]. In order to achieve this, one of the requirements of the individual lamina material is that it is highly anisotropic, making carbon fibre/epoxy resin a more suitable choice than either Kevlar/epoxy resin or glass fibre/epoxy resin, though all three material combinations have been investigated [**93–95**]. The majority of research work has been carried out on the carbon fibre composites, though, and is now concentrating on looking at how the properties of the laminates are affected.

Fracture toughness studies have shown that there are some enhancements and that the fracture itself tends to be cleaner [**92**]. Some very interesting effects have also been found when static indentation and low velocity impact of the laminates have been investigated [**96**]. These properties were evaluated in comparison with laminates having near zero and large positive Poisson's ratio values. The auxetic laminates show higher loads to first failure with enhanced energy absorption in both cases. The statically tested specimens also sustain higher loads with the onset of damage and absorb more energy to catastrophic failure (Fig. 8). This is a clear advantage over conventional stacking sequences when the problem of impact is considered, one which is a limiting factor in the use of composites in aerospace applications. Even more interesting, the initial damage sustained is much more localized for both static and low velocity impact testing, with a distinct lack of large delaminations in each case (Fig. 9). This means that less of the specimen needs to be repaired, another clear advantage in using auxetic materials.

A further way to make an auxetic fibre-reinforced composite is to use auxetic reinforcements. It has been suggested [**5**] that an auxetic fibre within a composite would resist fibre pull-out. When the fibre is pulled, it will expand and effectively lock into the matrix rather than contracting and pulling out easily as a conventional fibre would do. This is the same idea as the design of the press-fit fastener using auxetic copper foam [**57**] discussed above. With the invention of auxetic PP fibres [**75**], the concept of using auxetic fibres to increase fibre pull-out resistance has now been tested for an idealized composite system. Single fibre pull-out tests were carried out using auxetic PP fibres embedded in a softened epoxy resin and the concept has been clearly demonstrated. In comparative tests with specimens containing positive Poisson's ratio fibres, the auxetic fibre locking mechanism is shown to enable the specimen to carry more than twice the maximum load (Fig. 10). In terms of energy absorption, the auxetic fibre is up to three times more difficult to extract than the equivalent positive Poisson's ratio fibre [**97**].

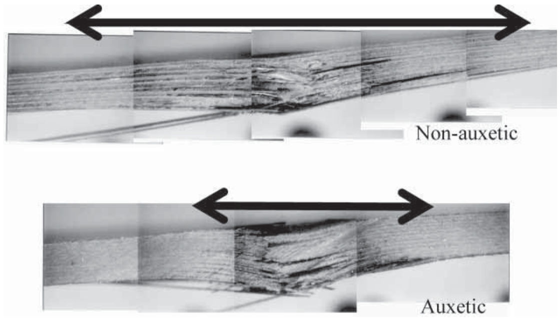


**Fig. 9** Sections showing static impact damage for non-auxetic and auxetic carbon–epoxy composite laminates. Arrows indicate extent of visible damage [**95**]

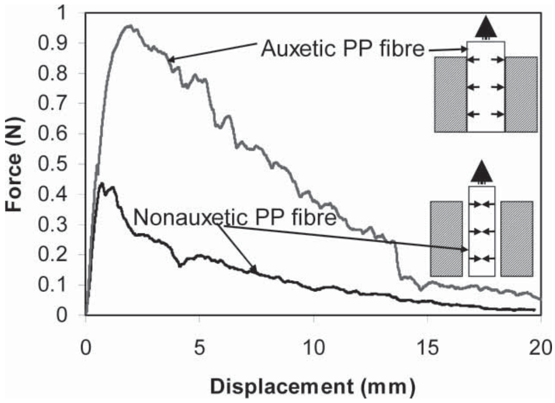


**Fig. 10** Single-fibre pull-out force–displacement data for auxetic and non-auxetic PP fibres embedded in epoxy resin. Inserts show auxetic fibre locking effect leading to enhanced fibre pull-out resistance [**96**]

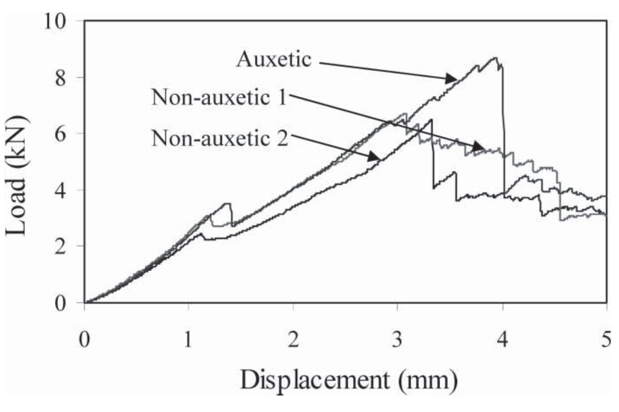


**Fig. 8** Static impact load–displacement data for auxetic and non-auxetic carbon–epoxy composite laminates [**95**]

## 5 SENSORS AND ACTUATORS

Auxetics are high volume change materials and so clearly have potential in sensor and actuator applications. Highly anisotropic auxetic materials are known with $\nu < -1$ (e.g. expanded PTFE [**60**]) leading to the possibility of a strain amplification device where the transverse strain is much greater than the longitudinal strain being measured. The use of auxetic cubic elemental metals as electrodes sandwiching a piezoelectric polymer has been proposed to give a two-fold increase in piezoelectric device sensitivity [**10**].

The use of an auxetic polymer matrix in a piezoelectric composite device has been proposed [**98**] to maximize the acoustic-to-electrical energy conversion. Under compression loading on the surface of the device the lateral contraction of the auxetic matrix allows enhanced lateral expansion of the embedded piezoelectric ceramic rods. Under hydrostatic compression loading, the auxetic matrix converts the lateral compression force into an additional compression force along the axis of the ceramic rods to augment the direct compression force in this direction. The high shear modulus with respect to bulk modulus, which is a consequence of a negative Poisson's ratio, enables efficient conversion of incident stresses on the polymer to lateral stresses acting on the ceramic rods. Piezoelectric composite devices are used in hydrophone and ultrasonic imaging applications and the use of an auxetic matrix has been predicted to lead to very significant (one to two orders of magnitude) increases in device sensitivity.

Finally, in this section, auxetic materials and structures can act as the substrate carrier for sensing and actuating devices. For example, piezoceramic sensors and/or actuators on a thin dielectric film can be attached to the ribs of an auxetic honeycomb core in a sandwich panel construction to provide non-destructive structural health monitoring capabilities.

## 6 CONCLUDING REMARKS

This review has covered aspects of auxetic materials that are considered most relevant to aerospace engineering applications. A range of natural and synthetic auxetic materials are now known and an increasing number of property enhancements have been predicted and confirmed experimentally. The potential exists to develop auxetic materials-based composites and related technologies for aerospace materials and systems having reduced cost, materials usage, and improved performance envelopes (impact, failure resistance, energy absorption, complex curvatures, structural health monitoring, and adaptive and deployable structures) leading to reduced fuel consumption and emissions.

In the UK the potential for these materials has been recognized in the form of the government-funded (Engineering and Physical Science Research Council) Auxetic Materials Network (AuxetNet) [**99**] and in national exercises such as the Materials Foresight Panel Report into Smart Materials and Systems [**100**]. Consequently major consortia are now in place performing the next stage of research activities to bring the potential of auxetic materials into commercial reality in aerospace, marine, and other sectors. Examples include a UK Department of Trade and Industry (DTI) funded consortium investigating each aspect of the sandwich panel construction shown in Fig. 2 (auxetic laminates, cores, fibres, and adhesives) [**101**] and a European Commission Framework Programme 6 (FP6) funded consortium investigating the development of chiral honeycomb core materials for load bearing and structural health monitoring capabilities [**102**].

## REFERENCES

1 **Marsh, G.** Airframers exploit composites in battle for supremacy. *Reinf. Plast.*, 2005, **49**(3), 26–32.
2 **Marsh, G.** Farnborough 2004 – good prospects for aerospace composites. *Reinf. Plast.*, 2004, **48**(8), 42–46.
3 **Borchardt, J. K.** Unmanned aerial vehicles spur composites use. *Reinf. Plast.*, 2004, **48**(4), 28–31.
4 **Evans, K. E., Nkansah, M., Hutchison, I. J.,** and **Rogers, S. C.** Molecular network design. *Nature*, 1991, **353**, 124.
5 **Evans, K. E.** Tailoring the Poisson's ratio. *Chem. Ind.* 1990, **20**, 654–657.
6 **Gunton, D. J.** and **Saunders, G. A.** The Young's modulus and Poisson's ratio of arsenic, antimony and bismuth. *J. Mater. Sci*, 1972, **7**, 1061–1068.
7 **Li, Y.** The anisotropy of Poisson's ratio, Young's modulus and shear modulus in hexagonal materials. *Phys. Status. Solidi B*, 1976, **38**, 171–175.
8 **Yeganeh-Haeri, Y., Weidner, D.J.,** and **Parise J. B.** Elasticity of $\alpha$-cristobalite: a silicon dioxide with a negative Poisson's ratio. *Science*, 1992, **257**, 650–652.
9 **Love, A. E. H.** A *treatise on the mathematical theory of elasticity*, 4th edition, 1927, p. 163 (Cambridge University Press, Cambridge).
10 **Baughman, R. H., Shacklette, J. M., Zakhidov, A. A.,** and **Stafstrom, S.** Negative Poisson's ratios as a common feature of cubic metals. *Nature*, 1998, **392**, 362–365.
11 **Veronda, D. R.** and **Westmann, R. A.** Mechanical characterization of skin – finite deformations. *J. Biomech.*, 1970, **3**, 111–124.
12 **Frohlich, L. M., Labarbera, M.,** and **Stevens, W. P.** Poisson's ratio of a crossed fibre sheath: the skin of aquatic salamanders. *J. Zool. Lond.*,1994, **232**, 231–252.
13 **Lees, C., Vincent, J. E. V.,** and **Hillerton, J. E.** Poisson's ratio in skin. *Biomed. Mater. Eng.*, 1991, **1**, 19–23.
14 **Williams, J. L.** and **Lewis, J. L.** Properties and an anisotropic model of cancellous bone from the proximal tibial epiphysis. *Trans. ASME, J. Biomech. Eng.*, 1982, **104**, 5–56.

15 **Lakes, R.** Foam structures with a negative Poisson's ratio. *Science*, 1987, **235**, 1038–1040.

16 **Gibson, L. J., Ashby, M. F., Schajer, G. S.,** and **Robertson, C. I.** The mechanics of two-dimensional cellular solids. *Proc. R. Soc. Lond.*, 1982, **A382**, 25–42.

17 **Almgren, R. F.** An isotropic three-dimensional structure with Poisson's ratio = 1. *J. Elast.*, 1985, **15**, 427–430.

18 **Kolpakov, A. G.** On the determination of the averaged moduli of elastic gridworks. *Prikl. Mat. Mekh.*, 1985, **59**, 969–977.

19 **Gibson, L. J.** and **Ashby, M. F.** *Cellular solids: structure and properties*, 1988 (Pergamon Press, London).

20 **Evans, K. E., Alderson, A.,** and **Christian, F. R.** Auxetic 2-dimensional polymer networks – an example of tailoring geometry for specific mechanical-properties. *J. Chem. Soc. Faraday Trans.*, 1995, **91**, 2671–2680.

21 **Masters, I. G.** and **Evans K. E.** Models for the elastic deformation of honeycombs. *Compos. Struct.*, 1997, **35**, 403–422.

22 **Evans, K. E.** Design of doubly-curved sandwich panels with honeycomb cores. *Compos. Struct.*, 1990, **17**, 95.

23 **Smith, F. C., Scarpa, F.,** and **Chambers, B.** The electromagnetic properties of re-entrant dielectric honeycombs. *IEEE Microw. Guided Wave Lett.*, 2000, **10**(11), 451–453.

24 **Ruzzene, M.** and **Scarpa, F.** Directional and band-gap behaviour of periodic auxetic lattices. *Phys. Status Solidi B*, 2005, **242**, 665–680.

25 **Prall, D.** and **Lakes, R.** Properties of a chiral honeycomb with Poisson's ratio –1. *Int. J. Mech. Sci.*, 1996, **39**, 305–314.

26 **Theocaris, P. S., Stavroulakis, G. E.,** and **Panagiotopoulos, P. D.** Negative Poisson's ratios in composites with star-shaped inclusions: a numerical homogenization approach. *Arch. Appl. Mech.*, 1997, **67**(4), 274–286.

27 **Larsen, U. D., Sigmund, O.,** and **Bouwstra, S.** Design and fabrication of compliant micromechanisms and structures with negative Poisson's ratio. *J. Microelectromech. Syst.*, 1997, **6**, 99–106.

28 **Paulhac, A., Perrot, D., Scarpa, F.,** and **Yates, J. R.** Flatwise compressive behaviour of novel chiral honeycomb concept. DFC-7 Conference, Sheffield, 22–24 May 2003.

29 **Spadoni, A., Ruzzene, M.,** and **Scarpa, F.** Global and local linear buckling behaviour of a chiral cellular structure. *Phys. Status Solidi B*, 2005, **242**, 695–709.

30 **Paulhac, A., Scarpa, F., Perrot, D.,** and **Yates, J. R.** Transverse shear strength of chiral cellular core. In Proceedings of ICEM12, Bari, Italy, 29 August to 1 September 2004.

31 **Scarpa, F. L., Hassan, M. H.,** and **Ruzzene, M.** Modelling and testing of shape memory alloy chiral honeycomb structures. In Proceedings of the SPIE International Society for Optical Engineering Smart Structures and Materials 2006: Active Materials: Behaviour and Mechanics, 2006, vol. 6170.

32 **Hassan, M. R., Scarpa, F., Mohammed, N. A.,** and **Ancrenaz, Y.** Conventional and auxetic SMA cellular structures. *ASME Aerosp. Div. Publ. AD*, 2005, **70AD**, 451–456.

33 **Bornengo, D., Scarpa, F.,** and **Remillat, C.** Evaluation of hexagonal chiral structure for morphing airfoil concept. *Proc. IMechE, Part G: J. Aerospace Engineering*, 2005, **219**(3), 185–192.

34 **Spadoni, A., Ruzzene, M.,** and **Scarpa, F.** Dynamic response of chiral truss-core assemblies. *J. Intell. Mater. Syst. Struct.*, 2006, **17**(11), 941–952.

35 **Jackman, R. J., Brittain, S. T., Adams, A., Prentiss, M. G.,** and **Whitesides, G. M.** Design and fabrication of topologically complex, three-dimensional microstructures. *Science*, 1998, **280**, 2089–2091.

36 **Alderson, A., Rasburn, J., Ameer-Beg, S., Mullarkey, P. G., Perrie, W.,** and **Evans, K. E.** An auxetic filter: a tuneable filter displaying enhanced size selectivity or de-fouling properties. *Ind. Eng. Chem. Res.*, 2000, **39**, 654–665.

37 **Rasburn, J., Alderson, A., Ameer-Beg, S., Mullarkey, P. G., Perrie, W.,** and **Evans, K. E.** Auxetic structures for variable permeability systems. *AIChE J.*, 2001, **47**(11), 2623–2626.

38 **Alderson, A., Rasburn, J., Evans, K. E.,** and **Grima, J. N.** Auxetic polymeric filters display enhanced de-fouling and pressure-compensation properties. *Memb. Technol.*, 2001, **137**, 6–8.

39 **Friis, E. A., Lakes, R. S.,** and **Park, J. B.** Negative Poisson's ratio polymeric and metallic behaviour. *J. Mater. Sci.*, 1988, **23**, 4406–4414.

40 **Loureiro, M. A.** and **Lakes, R. S.** Scale-up of transformation of negative Poisson's ratio foam: slabs. *Cell. Polym.*, 1997, **16**(5), 349–363.

41 **Chan, N.** and **Evans, K. E.** Fabrication methods for auxetic foams. *J. Mater. Sci.* 1997, **32**(22), 5945–5953.

42 **Alderson, A., Alderson, K. L., Davies, P. J.,** and **Smart G. M.** The effects of processing on the topology and mechanical properties of negative Poisson's ratio foams. In Proceedings of the ASME Aerospace Division 2005, 2005, vol. 70AD, p. 503 (American Society of Mechanical Engineers, Aerospace Division (Publication) AD).

43 **Martz, E. O., Lee, T., Lakes, R. S., Goel, V. K.,** and **Park, J. B.** Re-entrant transformation methods in closed cell foams. *Cell. Polym.* 1996, **15**(4), 229–249.

44 **Wang, Y. C., Lakes, R.,** and **Butenhoff, A.** Influence of cell size on re-entrant transformation of negative Poisson's ratio reticulated polyurethane foams. *Cell. Polym.*, 2001, **20**(6), 373–385.

45 **Alderson, A.** A triumph of lateral thought. *Chem. Ind.*, 1999, **10**, 384–391.

46 **Lakes, R. S.** and **Elms, K.** Indentability of conventional and negative Poisson's ratio foams. *J. Compos. Mater.*, 1993, **27**, 1193–1202.

47 **Chan, N.** and **Evans, K. E.** Indentation resilience of conventional and auxetic foams. *J. Cell. Plast.* 1998, **34**(3), 231–260.

48 **Choi, J. B.** and **Lakes, R. S.** Nonlinear properties of polymer cellular materials with a negative Poisson's ratio. *J. Mater. Sci.*, 1992, **27**, 5375–4684.

49 **Choi, J. B.** and **Lakes, R. S.** Fracture toughness of re-entrant foam materials with a negative Poisson's ratio: experiment and analysis. *Int. J. Fract.*, 1996, **80**, 73–83.

50 **Howell, B., Prendergast, P.,** and **Hansen, L.** Acoustic behaviour of negative Poisson's ratio materials. DTRC-SME-91/01, David Taylor Research Centre, Annapolis, MD, 1991.

51 **Chen, C. P.** and **Lakes, R. S.** Micromechanical analysis of dynamic behavior of conventional and negative Poisson's ratio foams. *J. Eng. Mater. Technol.*, 1996, **118**(3), 285–288.

52 **Lowe, A.** and **Lakes, R. S.** Negative Poisson's ratio foam as seat cushion material. *Cell. Polym.*, 2000, **19**(3), 157–167.

53 **Lipsett, A. W.** and **Beltzer, A. I.** Reexamination of dynamic problems of elasticity for negative Poisson's ratio. *J. Acoust. Soc. Am.*, 1988, **84**(6), 2179–2186.

54 **Chen, C. P.** and **Lakes, R. S.** Dynamic wave dispersion and loss properties of conventional and negative Poisson's ratio polymeric cellular material. *Cell. Polym.*, 1989, **8**, 343–359.

55 **Scarpa, F., Pastorino, P., Garelli, A., Patsias, S.,** and **Ruzzene, M.** Auxetic compliant and flexible PU foams: static and dynamic properties. *Phys. Status Solidi B*, 2005, **242**, 681–694.

56 **Alderson, A., Rasburn, J.,** and **Evans, K. E.** Mass transport properties of auxetic (negative Poisson's ratio) foams. *Phys. Status Solidi B*, 2007, **244**(3), 817–827.

57 **Choi, J. B.** and **Lakes, R. S.** Design of a fastener based on negative Poisson's ratio foam. *Cell. Polym.*, 1991, **10**, 205–212.

58 **Scarpa, F.** and **Smith, F. C.** Passive and MR fluid-coated auxetic PU foam – mechanical, acoustic and electromagnetic properties. *J. Intell. Mater. Syst. Struct.*, 2004, **15**(12), 973–979.

59 **Bullogh, W. A.** and **Scarpa, F.** Electrically controlled extension effects in soft solids. *Int. J. Mod. Phys. B*, 2005, **19**(7–9), 1655–1660.

60 **Caddock, B. D.** and **Evans, K. E.** Microporous materials with negative Poisson's ratios. I: Microstructure and mechanical properties. *J. Phys. D: Appl. Phys.*, 1989, **22**, 1877–1882.

61 **Evans, K. E.** and **Caddock, B. D.** Microporous materials with negative Poisson's ratios. II: Mechanisms and interpretation. *J. Phys. D: Appl. Phys.*, 1989, **22**, 1883–1887.

62 **Alderson, A.** and **Evans, K. E.** Microstructural modelling of auxetic microporous polymers. *J. Mater. Sci.*, 1995, **30**, 3319–3332.

63 **Alderson, A.** and **Evans, K. E.** Modelling concurrent deformation mechanisms in auxetic microporous polymers. *J. Mater. Sci.*, 1997, **32**, 2797–2809.

64 **Pickles, A. P., Webber, R. S., Alderson, K. L., Neale, P. J.,** and **Evans, K. E.** The effect of the processing parameters on the fabrication of auxetic polyethylene. 1: The effect of compaction conditions. *J. Mater. Sci.*, 1995, **30**, 4059–4068.

65 **Alderson, K. L., Kettle, A. P., Neale, P. J., Pickles, A. P.,** and **Evans, K. E.** The effect of the processing parameters on the fabrication of auxetic polyethylene. 2: The effect of sintering time and temperature. *J. Mater. Sci.*, 1995, **30**, 4069–4075.

66 **Neale, P. J., Pickles, A. P., Alderson, K. L.,** and **Evans, K. E.** The effect of the processing parameters on the fabrication of auxetic polyethylene. 3: The effect of extrusion conditions. *J. Mater. Sci.*, 1995, **30**, 4087–4094.

67 **Alderson, K. L.** and **Evans, K. E.** The fabrication of microporous polyethylene having a negative Poisson's ratio. *Polymer*, 1992, **33**, 4435–4438.

68 **Pickles, A. P., Alderson, K. L.,** and **Evans, K. E.** The effects of powder morphology on the processing of auxetic polyproylene. *Polym. Eng. Sci.*, 1996, **36**(5), 636–642.

69 **Alderson, K. L., Alderson, A., Webber, R. S.,** and **Evans, K. E.** Evidence for uniaxial drawing in the fibrillated microstructure of auxetic polymers. *J. Mater. Sci. Lett.*, 1998, **17**, 1415–1419.

70 **Webber, R. S., Alderson, K. L.,** and **Evans, K. E.** Novel variations in the microstructure of the auxetic microporous ultra high molecular weight polyethylene. Part 1. Processing and microstructure. *Polym. Eng. Sci.*, 2000, **40**(8), 1894–1905.

71 **Alderson, K. L., Webber, R. S.,** and **Evans, K. E.** Novel variations in the microstructure of the auxetic microporous ultra high molecular weight polyethylene. Part 2. Mechanical properties. *Polym. Eng. Sci.*, 2000, **40**(8), 1906–1914.

72 **Alderson, K. L., Webber, R. S., Kettle, A. P.,** and **Evans, K. E.** A novel fabrication route for auxetic polyethylene. Part 1: processing and microstructure. *Polym. Eng. Sci.*, 2005, **45**(4), 568–578.

73 **Alderson, K. L., Fitzgerald, A. F.,** and **Evans, K. E.** The strain dependent indentation resilience of auxetic microporous polyethylene. *J. Mater. Sci.*, 2000, **35**, 4039–4047.

74 **Alderson, K. L., Webber, R. S., Mohammed, U. F., Murphy, E.,** and **Evans K. E.** An experimental study of ultrasonic attenuation in microporous polyethylene. *Appl. Acoust.*, 1997, **50**(1), 23–33.

75 **Alderson, K. L., Alderson, A., Smart, G., Simkins, V. R.,** and **Davies, P. J.** Auxetic polypropylene fibres. Part 1. Manufacture and characterisation. *Plast. Rubbers Compos.*, 2002, **31**(8), 344–349.

76 **Alderson, A., Ravirala, N., Alderson, K. L.,** and **Davies, P. J.** Negative Poisson's ratio polyester fibers. *Text. Res. J.*, 2006, **76**(7), 540–546.

77 **Ravirala, N., Alderson, A., Alderson, K. L.,** and **Davies, P. J.** Expanding the range of auxetic products using a novel melt spinning route. *Phys. Status Solidi B*, 2005, **242**(3), 653–664.

78 **Alderson, A.** and **Alderson, K. L.** Expanding materials and applications: exploiting auxetic textiles. *Tech. Text. Int.*, 2005, **14**(6) 29–34.

79 **Ravirala, N., Alderson, A., Alderson, K. L.,** and **Davies, P. J.** Auxetic polypropylene films. *Polym. Eng. Sci.*, 2005, **45**(4), 517–528.

80 **Ogi, H., Fukunaga, M., Hirao, M.,** and **Ledbetter, H.** Elastic constants, internal friction, and piezoelectric coefficient of $\alpha$-$TeO_2$. *Phys. Rev. B*, 2004, **69**(2), 024104-1–8.

81 **Wojciechowski, K. W.** Constant thermodynamic tension Monte Carlo studies of elastic properties of a two-dimensional system of hard cyclic hexamers. *Mol. Phys.*, 1987, **61**, 1247–1258.

82 **Wojciechowski, K. W.** Non-chiral molecular model of negative Poisson's ratio in two dimensions. *J. Phys. A: Math. Gen.*, 2003, **36**(47), 11765–11778.

83 **Baughman, R. H.** and **Galvao, D. S.** Crystalline networks with unusual predicted mechanical and thermal properties. *Nature*, 1993, **365**, 735–737.

84 **Grima, J. N., Jackson, R., Alderson, A.,** and **Evans, K. E.** Do zeolites have negative Poisson's ratios? *Adv. Mater.*, 2000, **12**(24), 1912–1918.

85 **Evans, K. E., Alderson, A.,** and **Christian, F. R.** Auxetic two-dimensional polymer networks: an example of tailoring geometry for specific mechanical properties. *J. Chem. Soc. Faraday Trans.*, 1995, **91**, 2671–2680.

86 **Attenborough, E. R., Evans, K. E., Alderson, A., Eggen, B. R.,** and **Heggie, M. I.** Tailoring the elastic constants of two and three dimensional molecular networks. In Proceedings of the 10th International Conference on Deformation, Yield and Fracture of Polymers, Cambridge, UK, 1997.

87 **Alderson, A., Davies, P. J., Williams, M. R., Evans, K. E., Alderson, K. L.,** and **Grima, J. N.** Modelling of the mechanical and mass transport properties of auxetic molecular sieves: an idealised organic (polymeric honeycomb) host-guest system. *Mol. Simul.*, 2005, **31**(13), 897–905.

88 **He, C., Liu, P.,** and **Griffin. A. C.** Toward negative Poisson ratio polymers through molecular design. *Macromolecules*, 1998, **31**, 3145–3147.

89 **He, C., Liu, P., McMullan, P. J.,** and **Griffin, A. C.** Towards molecular auxetics: main chain liquid crystalline polymers consisting of laterally attached paraquaterphenyls. *Phys. Status Solidi B*, 2005, **242**, 576–584.

90 **Aldred, P.** and **Moratti, S. C.** Dynamic simulations of potentially auxetic liquid-crystalline polymers incorporating swivelling mesogens. *Mol. Simul.*, 2005, **31**(13), 883–887.

91 **Herakovich, C.** Composite Laminates with negative through-the-thickness Poisson's ratios. *J. Comp. Mat.*, 1984, **18**, 447–455.

92 **Chandhuri, J.** and **Jang, Q.** Effect of special orientation on the fracture behaviour of graphite/epoxy laminates. In Proceedings of the American Society for Composite 3rd Technical Conference (Eds J. C. Sefaris and J. T. Quinlivan), Seattle, USA, p. 701 (Technomic Publ. Co. Inc., Lancaster, USA).

93 **Clarke, J. F., Duckett, R. A., Hine, P. J., Hutchinson, I. J.,** and **Ward, I. M.** Negative Poisson's ratio in angle ply laminates: theory and experiment. *Composites*, 1994, **25**(9), 863–868.

94 **Al-Khalil, M. F. S.** *Strength of filamnet wound structures under complex stresses*. PhD Thesis, University of Manchester, 1990.

95 **Zhang, R., Yeh, H.-L.,** and **Yeh, H.-Y.** A preliminary study of negative Poisson's ratio of laminated fiber reinforced composites. *J. Reinf. Plast. Compos.*, 1988, **17**(18), 1651–1664.

96 **Alderson, K. L., Simkins, V. R., Coenen, V. L., Davies, P. J., Alderson, A.,** and **Evans, K. E.** How to make an auxetic composite. *Phys. Status Solidi B*, 2005, **242**, 509–518.

97 **Simkins, V. R., Alderson, A., Davies, P. J.,** and **Alderson, K. L.** Single fibre pullout tests on auxetic polymeric fibres. *J. Mater. Sci.*, 2005, **40**, 4355–4364.

98 **Smith, W.A.** Optimizing electromechanical coupling in piezeocomposites using polymers with negative Poisson's ratio. In Proceedings of IEEE Ultrasonics Symposium, Florida, USA, 1991, vol. 1, pp. 661–666 (IEEE).

99 Auxetic Materials Network, available from www.auxetnet.org.uk.

100 Smart materials for the 21st century. Materials Foresight Report No. FMP/03/04/IOM3. The Institute of Materials, Minerals and Mining, Foresight Smart Materials Taskforce, 2003.

101 http://www.technologyprogramme.org.uk/site/publicRpts/default.ctm?subcat=publicRpt3&ProjID=454741.

102 http://cordis.europe.eu/fetch?CALLER=FP6_PROJ&ACTION=D&RCN=75361&DOC=1&CAT=PROJ&QUERY=7.


## APPENDIX

### Notation

| | |
|---|---|
| $E$ | Young's modulus |
| $G$ | shear modulus |
| $\nu$ | Poisson's ratio |