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Procedia Engineering 72 (2014) 453 – 458
Procedia Engineering
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The 2014 conference of the International Sports Engineering Association

Auxetic materials for sports applications

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Abstract

In this paper, the auxetic effect is introduced, the range of auxetic materials is briefly reviewed, and research demonstrating benefits having potential in sports applications is highlighted. These include the use of auxetic materials in impact protector devices (pads, gloves, helmets and mats) exploiting better conformability for comfort and support, and enhanced energy absorption for lighter and/or thinner components. FE simulations are reported for a new type of auxetic honeycomb having potential in helmet applications, along with indentation testing of auxetic and non-auxetic foams for assessment in protective pads and running shoes applications, for example.

Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University

Keywords: Auxetic; negative Poisson's ratio; mechanical properties; honeycomb; foam

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Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University
doi:10.1016/j.proeng.2014.06.079

1. Introduction

Auxetic materials are fascinating materials which, when placed under tension in one direction, become thicker in one or more perpendicular directions (Fig. 1). In other words, an auxetic material possesses a negative value of Poisson’s ratio (Evans et al. (1991)).

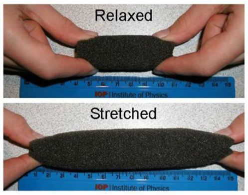

Fig. 1. Auxetic material

Fig. 2. Curvature of auxetic and non-auxetic materials

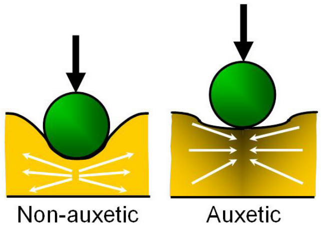

Fig. 3. Indentation response of non-auxetic and auxetic materials

Auxetic metals, polymers, composites, textiles and ceramics are known, spanning the nanoscale to the macroscale, in both natural and man-made forms. They are attracting interest due to their unusual mechanical response, and also because they offer a route to attaining extreme (high or low) values of other material properties not easily achievable in conventional materials. Examples include synclastic (dome-shape) curvature when subject to a bending moment (Fig. 2), enhanced indentation resistance (Fig. 3), fracture toughness, and vibration damping, and, in the case of porous auxetic materials, dramatic porosity variation when stretched. The reader is referred to reviews by Evans and Alderson (2000), Alderson and Alderson (2007), Liu and Hu (2010), and Greaves et al. (2011).

In this paper the authors focus on the potential of auxetic honeycombs and foams in sports applications. One of the first examples of an auxetic honeycomb was the re-entrant hexagonal honeycomb deforming by flexing and/or rotation (hinging) of the honeycomb ribs (Fig. 4a; Gibson et al. (1982)). Alternative honeycomb topologies, developed subsequently, include the 'arrowhead' geometry shown in Fig. 4b (Larsen et al. (1997)) and the family of chiral honeycombs comprising cylinders inter-connected by ligaments (e.g. Fig. 4c; Prall and Lakes (1996); Alderson et al. (2010a)). The cells of the arrowhead honeycomb open due to flexing and/or hinging of the ribs under tension to create the auxetic effect. In the chiral honeycombs, the auxetic effect arises due to cylinder rotation-induced bending of the ligaments. The cylinders afford increased through-thickness compression properties, whilst the ligaments provide increased through-thickness shear resistance.

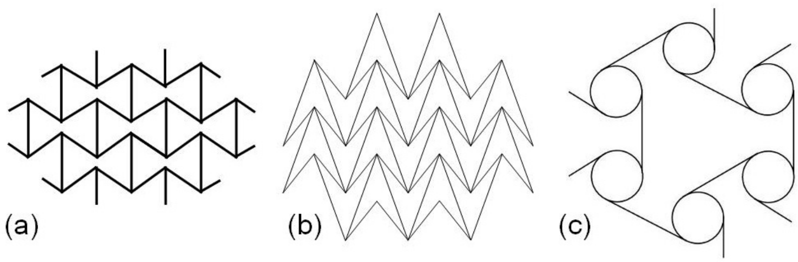

Fig. 4. Auxetic honeycomb motifs: (a) re-entrant hexagonal; (b) arrowhead; (c) chiral ('anti-trichiral')

The particular chiral honeycomb shown in Fig. 4c displays auxetic behaviour in the short ligament limit for in-plane uniaxial loading, but anticlastic (saddle-shape) curvature characteristic of positive Poisson's ratio behaviour when bent out of plane (Alderson et al. (2010b)). This loading-dependent Poisson's ratio is a consequence of a cancellation of the cylinder rotation mechanism during bending: cylinder rotation due to tension on the top surface is opposed by cylinder rotation in the opposite sense caused by compression of the bottom surface of the honeycomb (Alderson et al. (2010b)). In pure bending, then, the honeycomb response is essentially reduced to that of the base hexagonal honeycomb motif (i.e. in the limit of zero cylinder radius), which is known to lead to positive Poisson's ratio when ligament flexing or hinging dominates (Gibson et al. (1982)). Chiral honeycombs displaying the auxetic effect for both in-plane and bending loads are achieved by arranging the cylinders on the base re-entrant motif shown in Fig. 4a (Alderson et al. (2010b)). This, then, allows the double-curvature required for dome-shape applications to be achieved naturally through the auxetic effect, whilst also exploiting the enhanced through-thickness compression and shear resistance properties of the cylinders and ligaments, respectively.

Auxetic foams were first made using a triaxial compression and heat treatment process by Lakes (1987). Auxetic foam displays synclastic curvature and improved resilience (Lakes (1987)), indentation resistance (Lakes and Elms (1993), Chan and Evans (1998)), shear resistance (Choi and Lakes (1992)), fracture toughness (Choi and Lakes (1992)) and vibration damping (Howell et al. (1991), Chen and Lakes (1996)).

Auxetic materials, therefore, have the potential to be used in a variety of sporting products, particularly safety equipment such as helmets and body armor exploiting better conformability for comfort and support, and enhanced energy absorption for lighter and/or thinner components. The authors report here the design of an alternative cylinder-ligament honeycomb comprising cylinders arranged on the tessellating arrowhead honeycomb motif (Fig. 4b). Selected results are also presented from a comprehensive investigation into the response of auxetic and non-auxetic foams to static indentation.

2. Auxetic 'chiral-arrowhead' honeycomb

The chiral arrowhead honeycomb is shown in Fig. 5a. The new cylinder-ligament honeycomb is achieved by locating cylinders at each junction connecting 4 tangentially attached ligaments in the arrowhead geometry of Fig. 4b. The honeycomb geometrical parameters (Fig. 5a insert) employed in the model were: l = 4.7 cm, m = 2.4cm, α = 30°, t = 0.1cm, d = 10cm (= depth) and r = 0.5 cm. Finite Element model simulations were performed using the ANSYS FE package, version 10.0. PLANE2 (linear elastic, solid) elements were employed in the simulations of the in-plane mechanical properties. Simulations were performed on an array of 9×9 unit cells. SHELL93 elements were employed in arrays of 5×9 unit cells in order to visualize the curvatures adopted by the honeycombs under out-of-plane bending. Loading and boundary conditions, and determination of strains, followed those adopted for the re-entrant chiral honeycomb simulations described in Alderson et al. (2010b). The Poisson's ratios were calculated from the slope of the transverse strain (ε_j) vs axial strain (ε_i) data: $\nu_{ij} = -(\varepsilon_j / \varepsilon_i)$, where i is the loading direction.

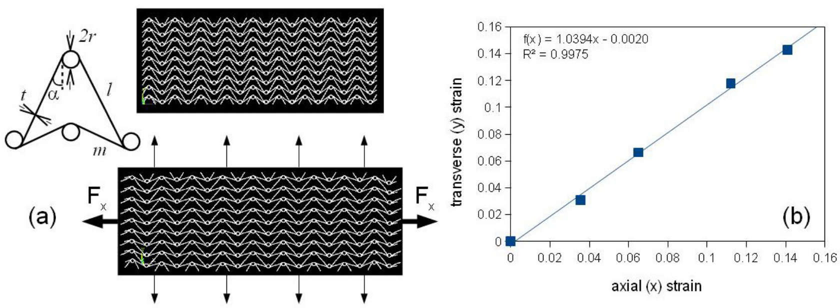

Fig. 5. 'Chiral arrowhead' honeycomb: (a) 9x9 unit cell FE model before and after stretching (insert: geometrical parameters); (b) transverse (y) strain vs axial (x) strain data

Fig. 5a shows the FE model array before and after tensile loading along the x (horizontal) direction and clearly demonstrates axial and transverse expansion. The slope of the transverse strain vs axial strain data (Fig. 5b) yields a predicted Poisson's ratio of ν_{xy} = -1.04. Out-of plane bending simulations showed characteristic synclastic curvature, confirming the auxetic effect is present in both in-plane stretching and out-of-plane bending (Fig. 6).

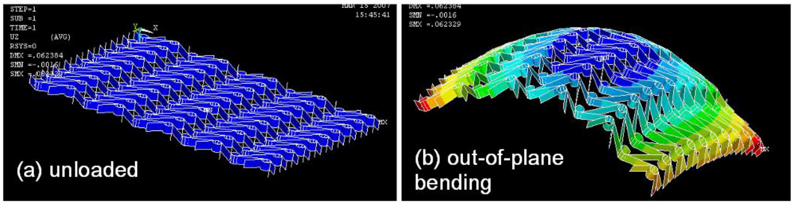

Fig. 6. 'Chiral arrowhead' honeycomb: 5x9 unit cell FE model (a) before and (b) after out-of-plane bending

3. Indentation response of Auxetic and Conventional open-cell polyurethane (PU) foam

The foam conversion process was based on the original thermo-mechanical method published by Lakes and co-workers (Friis et al. (1988)). Low-density PU foam (Custom Foams, designated by R45FR, 45 pores in^{-1}, density 26–32 kg m^{-3}) was cut into a cuboidal shape of size 100×100×100mm and placed inside a cuboidal hollow metal tube of size 65×67×67mm, with metal end plates attached, to achieve a triaxial compression on the foam. The mould containing the compressed foam was then placed in an oven at 190°C for 50 minutes. The mould was then removed from the oven, and the foam was removed from the mould and stretched gently by hand in each of the three directions twice at room temperature to avoid adhesion of the cell ribs. The foam was reinserted into the mould and placed back into the oven at 190°C for a further 20 minutes. The process was repeated for a second time, but with the oven temperature reduced to 100°C and for a heating time of just 10 minutes.

Mechanical properties characterization of the starting and converted foams was carried out using a MESSPHYSIK ME46-NG video extensometer to measure the axial and transverse strains in test specimens undergoing uniaxial compression. Tests were performed at a cross head speed of 2 mm/min in an Instron 3369 testing machine fitted with a 100N load cell. Indentation tests were performed to 10mm indentation on each of the 6 faces of each foam specimen. The same testing set-up and a range of indenters of different sizes and shapes were employed. The complete analysis from this comprehensive indentation investigation is beyond the scope of this paper and will be reported in a future publication. Here the authors report indentation results for a 12mm diameter steel ball indenter by way of example.

Typical stress-strain data for the unconverted and converted (auxetic) foam under uniaxial compression are shown in Fig. 7a. The unconverted foam displays an initially linear response before entering a plateau (reduced tangent modulus) region. The converted foam, on the other hand, is characterised by an initial response of lower modulus than the unconverted foam, which then increases in modulus and exhibits linear behaviour at intermediate and high applied strain. The auxetic foam is, therefore, more resilient under uniaxial compression.

The Poisson's ratios determined from the slope of the transverse strain vs axial strain data vary with strain, and display the anisotropy known to exist in these materials (Fig. 7b). There are 6 curves for each foam in Fig. 7b, corresponding to each of the directional Poisson's ratios ν_{xy}, ν_{xz}, ν_{yx}, ν_{yz}, ν_{zx} and ν_{zy}. The converted foam is confirmed to be auxetic, and in some directions undergoes a transition to positive Poisson's ratio response as compressive strain is increased. Despite having a lower initial average directional Young's modulus ($<E_i>$), the average directional strain energy density ($<U_i/V>$, where U is the strain energy and V is the foam volume) of the auxetic foam is similar to that of the conventional foam under compression to 15% strain (Table 1). This is due to the plateauing of the conventional foam stress-strain data at higher compression.

The similar average strain energy density values for the two foams under uniaxial compression contrasts with the average work required to indent the foams to a depth of 10mm ($<U_i^{ind}>$), determined from the area under the indentation force-displacement curve. The auxetic foam requires 220% the work required for the conventional foam (Table 1). The auxetic foam, therefore, clearly displays enhanced resistance to indentation (Fig. 7c shows the indentation load vs compression curves for indentation on each of the 6 faces for each foam). This is also evident by the average maximum indentation force (<F_i^{max}>) acting on the auxetic foam being 204% that on the conventional foam, and the average indentation depth of the auxetic foam at an indenter load of 2N (<D_i^{2N}>) being 53% that of the conventional foam. In addition to being more indentation resistant, the auxetic foam also absorbs significantly more energy than the conventional foam: the average energy absorbed by the auxetic foam (<$U_{abs\ i}^{ind}$>), determined from the area of the hysteresis loop, is 229% that absorbed by the conventional foam.

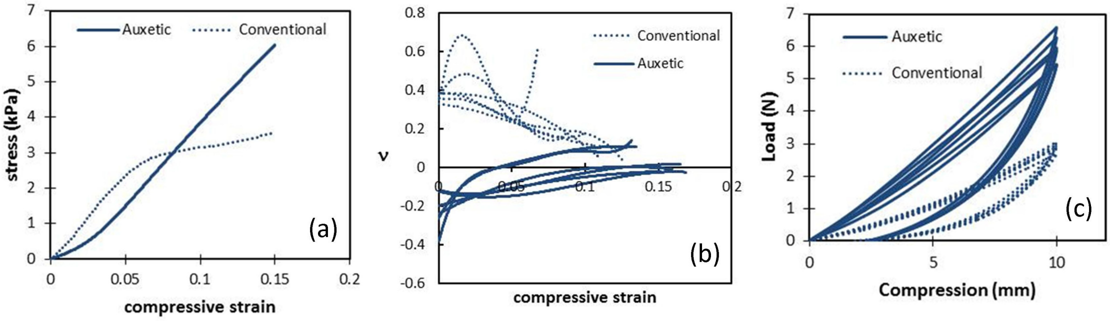

Fig. 7. Foam mechanical properties: (a) stress-strain and (b) Poisson's ratio vs strain data for unconverted (conventional) and converted (auxetic) foam; (c) indentation load vs compression

Table 1. Average foam directional mechanical properties.

Foam	Compression tests			Indentation tests			
	<E_i> (kPa)	<ν_{ij}>	<U_i/V> (J m^{-3})	<F_i^{max}> (N)	<D_i^{2N}> (mm)	<U_i^{ind}> (J)	<$U_{abs\_i}^{ind}$> (J)
Auxetic	14.7±4.1	-0.22±0.09	350±100	5.93±0.42	4.09±0.42	26.9±2.5	13.6±1.8
Conventional	37.5±1.5	+0.36±0.02	377±42	2.91±0.11	7.71±0.22	12.24±0.50	5.96±0.46

4. Discussion and conclusions

The authors have reported here FE simulations of a new cylinder-ligament honeycomb displaying auxetic behaviour in both uni-axial in-plane and out-of-plane bending loading. The synclastic curvature adopted by the honeycomb makes this system a candidate core material in sports helmet applications, for example. The material naturally adopts the double-curvature required of the helmet, whilst ensuring the cylinders incorporated in the honeycomb structure are always aligned normal to the curved surface to provide maximum resistance to through-thickness crushing or impact events.

The fabrication and mechanical testing of auxetic open-cell polymeric foams, made using Lakes' original thermo-mechanical route for the conversion of conventional starting foam, have also been reported. The converted foams have been confirmed to be auxetic, with an initial average directional Young's modulus approximately half that of the starting foam. However, the auxetic foams are shown to be more resilient under uniaxial compression and, therefore, display similar strain energy density, on average, to the starting foam under compression to 15% strain. This contrasts with a significantly higher (more than a factor of 2) amount of work required to indent the auxetic foam to a depth of 10mm using a ball indenter (with corresponding higher maximum indenter load, and lower displacement for a given indenter load). The auxetic foam is, therefore, more indentation resistant than the starting foam, and has also been shown to absorb more indentation energy (again by more than a factor of 2) than the starting foam. Auxetic foam is, therefore, shown to be an excellent candidate material for use in energy absorbing components and impact protectors, such as batting pads, batting gloves and football shin pads.

Gradient open-cell foams and honeycombs displaying the auxetic effect have recently been reported (Alderson et al. (2013)), Lira et al. (2011)). These materials possess regions of negative (auxetic) and positive (conventional) Poisson's ratio behaviour, and can be engineered to undergo dramatic shape changes upon simple stretching in one direction. The phrase *piezomorphic* materials has been introduced to describe these mechanically-triggered shape-change materials, and their use as adaptable space-filling liners in prosthetic limb sockets, for example, has been suggested (Alderson et al. (2013)). Within the context of the work presented here, they also offer the potential to optimise the design of cellular materials for sporting impact applications where it is possible some regions of sporting equipment may require different impact or curvature properties to other regions.

Other benefits of auxetic materials having potential in sports applications include the dramatic porosity variation displayed by porous auxetic materials when stretched (Alderson et al. (2000)). This provides a route to variable breathability materials for enhanced thermophysical comfort, and could enable storage-release functionality for controlled release of guest odour or antiperspirant agents during periods of high activity.

Acknowledgements

The authors acknowledge funding for the honeycomb simulations in work supported by the Technology Strategy Board under grant TP3/SMS/6/I/16293. The work on foams has been funded through the Marriott Trust of the Rotary Club, Bolton Le Moors.

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