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ScienceDirect

Procedia Engineering 147 (2016) 384 – 389

Procedia Engineering

www.elsevier.com/locate/procedia

11th conference of the International Sports Engineering Association, ISEA 2016

A comparison of novel and conventional fabrication methods for auxetic foams for sports safety applications

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Abstract

This study compares fabrication methods for auxetic foam intended for use in sports safety equipment. Thermo-mechanical conversion methods were applied using: i) cubic moulds (150x150x150 mm), ii) cuboidal moulds (150x150x30 mm) & iii) cuboidal moulds (150x150x30 mm) with through-thickness pins. The cuboidal moulds having one reduced dimension relative to the cubic moulds enable faster heat transfer and more consistent through-thickness compression to the foam during conversion. The through-thickness pins allow greater control of in-plane compression throughout the bulk of the converted foam. Samples were compared using: i) density measurements and measurements of total surface folding (length multiplied by depth), ii) quasi-static compressive load/unload tests to obtain specific strain energy, stress/strain relationship and Poisson's ratio, iii) impact testing on a bespoke drop rig based on a standard for cricket pads (BS 6183-3: 2000, EN 2001) at 5, 10 and 15 J & iv) microscopic images of dissected samples to confirm their auxetic (re-entrant) structure. Samples fabricated in cuboidal moulds show less variation in final density, axial compressive stiffness and specific strain energy between samples than those cut from monoliths fabricated in cubic moulds. Samples created with through-thickness pins exhibited reduced surface folding. Greater control over final properties paves the way for further work designing auxetic foams for sport safety equipment.

Peer-review under responsibility of the organizing committee of ISEA 2016
Keywords: Impact; protection; Poisson's ratio; manufacture; hysteresis

1. Introduction

Sporting personal protective equipment (PPE) typically includes a thin sheet of foam for energy absorption covered by a plastic shell for energy dissipation [1]. Auxetic open cell foams, having a negative Poisson's ratio, have been shown to increase impact force attenuation and resist 'bottoming out' when compared to their conventional open cell counterparts [2, 3]. Additional advantages of auxetic materials for application to PPE include their synclastic (domed) curvature, which could improve fit and therefore comfort [4, 5]. Previous work on samples sliced from large cubic auxetic monoliths showed variable improvements to impact force attenuation when compared to conventional open cell foams [6]. Individually fabricating thinner samples could help reduce variations and thin sheets having both curved and flat profiles have been fabricated using solid moulds [7] and vacuum bags [8]. However, auxetic foams typically display heterogeneous structure and properties, as observed, for example, through analysis of cellular structure using Digital Volume Correlation [9], and quasi-static stress-strain and Poisson's ratio responses [6, 10]. The heterogeneity arises due to variable compression levels and thermal gradients experienced by the foam in the typical thermo-mechanical conversion process [11], which involves compression and thermal softening of the parent conventional foam to create an inward folding cellular structure. Reported variations are most apparent in samples fabricated as large monoliths [12] and have an effect on impact force attenuation [6]. Pins have recently been used to successfully apply variable compression levels in the production of small gradient auxetic foam samples [13]. Here we investigate the use of pins to conversely control lateral compression of larger sheets to achieve improved uniformity of structure and properties. This study aims, then, to

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Peer-review under responsibility of the organizing committee of ISEA 2016
doi:10.1016/j.proeng.2016.06.323

compare previous methods (cutting samples from large fabricated auxetic monoliths) to samples fabricated individually in thin cuboidal moulds [6] and thin cuboidal moulds with through-thickness pins. Surface folding, density, quasi-static stress-strain relationships, Poisson's ratio and impact force attenuation of fabricated samples are compared.

2. Methods

2.1 Fabrication Process

A thermo-mechanical conversion process adapted from previous methods [6, 11] was applied to open cell R30 FR polyurethane foam (Custom Foams). Oversized foam samples were compressed into the three mould designs, creating; i) one 150x150x150 mm cubic monolith ii) three 150x150x30 mm cuboids and iii) three 150x150x30 mm cuboids fabricated using 2.5 mm diameter metallic through-thickness pins to control lateral compression (Figure 1). These moulds will be referred to as the cubic mould, the cuboidal mould and the pinned mould respectively. Volumetric compression ratio (VCR) is the initial volume divided by the final volume. An isotropic VCR of 2.9 was applied to all samples by using starting (unconverted) foams having edge lengths greater than the mould dimensions by a factor of 1.4. Moulds were lubricated with olive oil prior to foam insertion to reduce surface friction. For pinned conversions, sixteen pins were inserted with 43 mm spacing into the foam (Figure 1a). These pins were then passed through holes at 30 mm spacing in the lower u-shape section of a 2-part mould, then into corresponding holes in a wooden block placed below to secure them in place (Figure 1b). Pins in the central square were inserted first, followed by outer corners then the remaining 8 pins. Spacers located between the mould and wooden block allowed visual inspection when inserting the rods into the holes. Finally, the upper u-shape section of the mould was fitted, allowing the wooden block to be removed (Figure 1c). Figure 1d shows a sample fabricated using through-thickness pins.

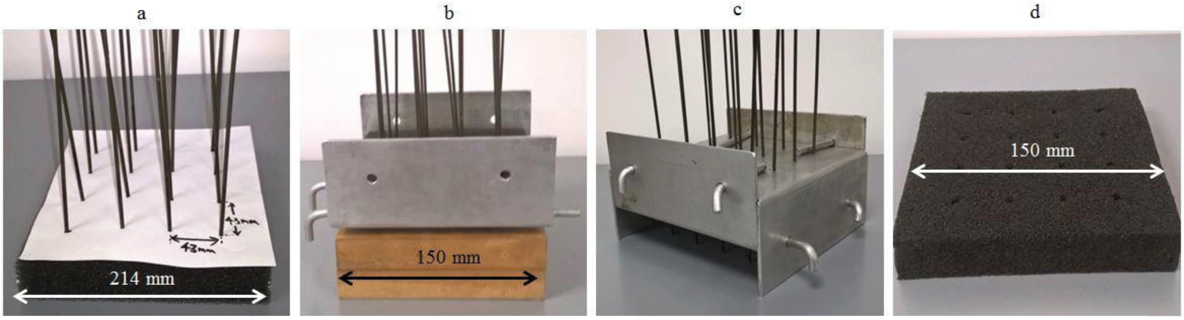

Figure 1 Photograph showing (a) Oversized foam cuboid with through-thickness pins inserted, (b) Insertion of pins and foam into lower section of mould, (c) Cuboidal mould assembly with through-thickness pins, d) Cuboidal auxetic sample fabricated with through-thickness pins.

The cubic mould was heated for two 35 minute periods at 180 °C, followed by a 35 minute annealing period at 100 °C to lock in the re-entrant structure, as per previous methods [6]. Foam was removed from the mould and gently stretched in all 3 orthogonal planes after each heating phase to reduce adhesion of cell ribs and surface creasing. After annealing, the foam was left to cool to ambient temperature in the mould. The fabricated cube was cut with a band saw (Bauer Maschinenbau) into five 30 mm thick slices to match individually fabricated cuboidal samples, with their thickness aligned to the foam rise direction. The heating process was adapted for individually fabricated cuboidal samples. Due to the reduced thickness of cuboidal and pinned moulds, the 35 minute heating and annealing periods were reduced to 25 minutes. Any through-thickness pins were removed after the first heating phase and not returned.

2.2. Material Classification

Surface creasing can be an issue with auxetic foams (particularly in larger conversions) and leads to internal flaws and inconsistencies [12]. To quantify flaws caused by each fabrication method without damaging the samples, the length and maximum depth of folds were measured. These were used to calculate mean fold area for fabricated samples. The density of each sample was also measured to calculate its final VCR.

Four load-unload tests were performed on all converted and three unconverted samples of equal dimensions (using an Instron 3367 mechanical testing machine with a 5 kN load cell and flat compression plates) up to 20%, 50% and 80% compressive engineering strain (6 mm, 15 mm and 24 mm displacement, respectively) at a displacement rate of 3 mm/minute. Samples were tested to 20%, 50% and 80% compressive Engineering strain on separate days to allow sufficient recovery. Mean specific strain energy absorbed (the area within the force-displacement hysteresis loop normalised to samples mass) was calculated and corrected for variations in thickness. Six pins (used as point markers) placed on the surface of each sample (with 30, 80 & 130 mm separations) were filmed using a high definition camera (Sony Handycam HFR-CX410) with a frame rate of 25 frames per second. Pins were tracked in a bespoke MATLAB algorithm to obtain true lateral strain (which analysed every 5th