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Varying the performance of helical auxetic yarns by altering component properties and geometry

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ABSTRACT

This paper presents a systematic study of the helical auxetic yarn (HAY) via careful in-house fabrication and characterisation of a wide range of polymeric fibres and yarns. It provides a better understanding of the auxetic behaviour of the HAY in order to tailor their properties for specific applications. The study focused on three parameters: component moduli, the core/wrap diameter ratio and the initial wrap angle. The results show that a larger difference in component moduli, a higher core/wrap diameter ratio and a lower initial wrap angle can produce a larger maximum negative Poisson's ratio value and thereby a better auxetic performance for HAYs. All three parameters could be carefully utilised when in combination to achieve the required auxetic behaviour of HAYs. Moreover, the instantaneous true Poisson's ratio analysis accurately presents the instantaneous behaviour of highly strain dependent HAYs.

1. Introduction

In comparison to conventional materials, auxetic materials exhibit a negative Poisson's ratio, they expand laterally when stretched and contract laterally when compressed [1,2]. Auxetic materials are of interest because of their capability to enhance mechanical properties such as shear modulus, indentation resistance, and fracture toughness [3]. As a consequence, they have potential in many practical applications such as impact absorbing foams, fasteners, composites, auxetic textiles for military use, sandwich panels for aircraft, biomedical and nanotechnology applications [3–8].

The helical auxetic yarn (HAY) [9] is a novel structure comprised of two components: an elastic core and a stiff wrap in the form of a helically wound structure, see Fig. 1. When a tensile load is applied the yarn becomes effectively wider, as the wrap straightens out and displaces the core, causing a lateral expansion of the core, and thereby exhibiting an auxetic effect. This type of structure has been considered for several applications, such as healthcare [10], body armour [9], blast curtains, and filtration [11]. According to previous studies [12–15], the auxetic behaviour of the HAY can be carefully controlled by selecting fibre diameters, component modulus, the initial geometry and also the applied strain. However, to date, the manufacture and characterisation of the HAY was limited to a narrow range of candidate core fibres, which did not enable the maximum advantage of the auxetic behaviour effect. Hence, only a narrow diameter range has been investigated in the previous studies [12–17]. This paper describes the expansion, optimisation and tailoring of the utilisation of the HAY through careful in-house fabrication and characterisation of a wide range of polymeric fibres and yarns. We focus here on the variation in component modulus, the core/wrap diameter ratio and the initial wrap angle on the auxetic behaviour of the HAY.

2. Methods

Extrusion was employed to fabricate cores of varying diameters. Elastollan® Thermoplastic polyurethane (TPU) – CA85A granules (polyester-based TPU) were purchased from BASF to fabricate monofilament core fibre. Monofilament core fibres with various diameters were fabricated using a Rondol (www.rondol.com) 18 mm diameter bench top single screw extruder (model-Linear 18). Ultra-high-molecular-weight polyethylene (UHMWPE) fibre and stainless steel wire utilised as the wrap fibres due to their high strength and modulus, were sourced from Monofil Technik. Accurate diameters of core and wrap fibres were measured by optical stereo microscope, see Table 1. Surface morphology of failed HAYs were characterised by Dino-Lite Pro (HR AD7013MZT) digital microscope and scanning electron microscope (SEM) (Hitachi S-3200N).

Helical auxetic yarns were fabricated using a bespoke spinner, which was developed and described in a previous study [13]. Typical properties for fibres and HAYs are presented in Table 1. Three

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Nomenclature

ε_x	engineering longitudinal strain
ε_y	engineering transverse strain
ε_x^{int}	instantaneous true longitudinal strain
ε_y^{int}	instantaneous true transverse strain
ν	Poisson's ratio
ν_{xy}	engineering Poisson's ratio
ν_{xy}^{int}	instantaneous true Poisson's ratio
θ	initial wrap angle (deg)
λ	cyclic pitch of wrap fibre (m)

types of monofilament core fibres and two types of wraps were utilised to manufacture HAYs. The wrap angle was only varied while using the largest core fibre to fabricate HAYs.

Tensile measurements of monofilament core, wrap fibres and HAYs were performed using previous described methods, and engineering longitudinal strain measurements of monofilament core fibres and HAYs were also computed using a previous described image analysis method [13]. Engineering transversal strain measurements of monofilament fibres and HAYs were carried out automatically with the assistance of image processing implemented in MatLab R2011b. For each image, the sample object (the ensemble of the core and wrap) is identified via Sobel edge detection [18] (which creates an image with an emphasis of edges and transitions), followed by morphological operations (dilate, fill and erode). This identification gives a binary image; one colour for the object and the other for the background. The upper and lower boundary curves of the resulting binary image are smoothed using a moving average filter. Local peaks of the upper smoothed boundary, and troughs of the lower smoothed boundary are then identified. To measure the time dependent transversal strain, a pair of local peaks and troughs is chosen at the first image to be that in the oscillation cycle on the wrap near the right end of the HAY.

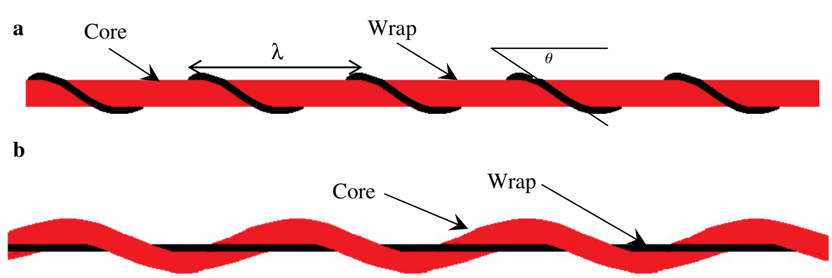

Fig. 1. Illustration of a HAY comprising a core and a helically wound wrap at initial angle θ: (a) HAY at zero strain and (b) HAY at maximum strain (after [12]).

Table 1
Typical properties for fibres and HAYs.

Sample	Type	TPU core (μm)	UHMWPE wrap (μm) (+/− 27 μm)	Stainless steel wrap (μm) (+/− 0.3 μm)	Initial wrap angle (°)	Young's modulus (MPa)	Tensile strength (MPa)
A	Fibre	394.5 ± 23.8	–	–	–	12.5 ± 2.2	–
B	Fibre	683.6 ± 30.5	–	–	–	14.7 ± 3.6	–
C	Fibre	1302.1 ± 23.4	–	–	–	14.8 ± 1.4	
D	Fibre	–	370	–	–	23,000 ± 3000	4300 ± 160
E	Wire	–	–	139.8	–	43,000 ± 1700	3600 ± 100
F	Helical auxetic yarn	394.5 ± 23.8	370	–	12.8 ± 1.8	–	–
G	Helical auxetic yarn	683.6 ± 30.5	370	–	12.4 ± 1.4	–	–
H	Helical auxetic yarn	1302.1 ± 23.4	370	–	12.5 ± 1.5	–	–
I	Helical auxetic yarn	1302.1 ± 23.4	370	–	20.6 ± 1.2	–	–
J	Helical auxetic yarn	1302.1 ± 23.4	370	–	30.9 ± 1.4	–	–
K	Helical auxetic yarn	1302.1 ± 23.4	370	–	40.7 ± 1.9	–	–
L	Helical auxetic yarn	394.5 ± 23.8	–	139.8	13.0 ± 0.4	–	–
M	Helical auxetic yarn	1302.1 ± 23.4	–	139.8	10.9 ± 1.5	–	–
N	Helical auxetic yarn	1302.1 ± 23.4	–	139.8	19.8 ± 1.1	–	–
O	Helical auxetic yarn	1302.1 ± 23.4	–	139.8	31.4 ± 1.5	–	–