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The variation in Poisson's ratio caused by interactions between core and wrap in helical composite auxetic yarns

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ABSTRACT

Materials with a negative Poisson's ratio are referred to as auxetic. One recently invented example of this is the helical auxetic yarn (HAY). This has been proved to successfully exhibit auxetic behaviour both as a yarn and when incorporated into fabric. The HAY is based on a double-helix geometry where a relatively stiffer 'wrap' is helically wound around a compliant core fibre. This paper studies the effect of the interaction between the core and the wrap fibre on the auxetic behaviour of the HAY, including the effect of their relative moduli. Assessment of the Poisson's ratio of the HAYs has revealed that an elevated difference in component moduli causes the wrap fibre embedding itself into the core fibre, thus decreasing the auxetic effect. Careful determination of an optimum core–wrap moduli ratio where the ratio is high enough to yield an auxetic effect and low enough to prevent the core-indentation effect can lead to the fabrication of a yarn with largest negative Poisson's ratio.

1. Introduction

'Auxetic' materials are a relatively new class of functional materials which exhibit negative Poisson's ratio; i.e. an applied tensile strain in the longitudinal direction results in a positive strain in the transverse direction [1]. Such materials have many benefits such as increased shear to tensile stiffness ratios, indentation resistance, energy absorption and the ability to form synclastic doubly-curved surfaces [2–4]. A range of auxetic materials have been discovered, fabricated and investigated during the last two decades, including auxetic cellular solids [5,6], auxetic microporous polymers [7,8], auxetic composites [9–11], molecular auxetic materials [1,12,13].

Hook et al. proposed a new geometry and composite for auxetic behaviour in the form of a helically wound yarn which can attain large negative Poisson's ratio, both by itself and in a textile [14]. This has been referred as the helical auxetic yarn (HAY), and may find applications in filtration [15] and healthcare [16]. Its basic structure and mechanics has been well investigated, both experimentally and theoretically, since its invention [10,11,17–19]. Owing to its wide variety of applications, research is continuing on improving its performance. Some more types of auxetic fibres have been fabricated by other researchers for textiles [20–22]. This study deals with some aspects of the HAY which reveals that an alteration of material parameters can cause large changes in its negative Poisson's ratio.

A HAY is composed of two conventional fibres in which a relatively stiffer and thinner "wrap" fibre is helically wound around a more compliant and thicker "core" fibre, as shown in Fig. 1a. On application of longitudinal strain, the difference in the modulus of elasticity and diameters of the two fibres causes lateral displacement of the core by the wrap, resulting in an overall lateral expansion of the yarn's maximal width. By selecting fibre diameters, moduli and the initial geometry of the HAY, a large negative Poisson's ratio can be generated.

The configuration of a HAY requires the core to be more flexible than the wrap. If the core is both compliant and elastomeric the core performs two functions: enabling large lateral deformation when strain is applied, and acting as a 'return spring' to recover its former position and reform the original helix in the wrap when the load is removed. However, with the compliancy of the core there is the possibility of generating an undesirable mechanism within the HAY. When the HAY is under tension the wrap may indent the surface of the core and embed itself into the core. As a consequence, there may be a reduction in the negative Poisson's ratio and hence the auxetic behaviour of the HAY. Some of the possible interactions are illustrated in Fig. 1b.

These core-indentation effects depend on the relative moduli of the core and wrap and, at large deformation, the extent to which the core remains elastic or goes plastic. In previous research

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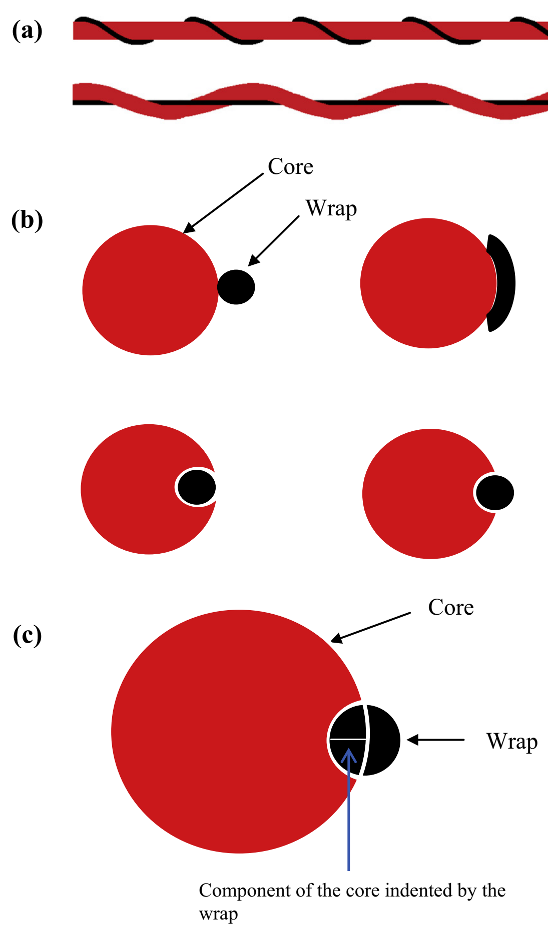

Fig. 1. (a) HAY at zero strain and at maximum strain. (b) Cross-section of the HAY (clockwise): Ideal case, the wrap spread around the core, partial core-indentation and entire core-indentation. (c) Component of the wrap embeded into the core.

studies, auxetic behaviour has been demonstrated by HAYs with varying ranges of core and wrap materials and has also been observed to be strongly dependent on relative component moduli. Sloan et al. fabricated a HAY using polyurethane fibre as the core (Young's modulus 30 MPa) and polyamide fibre as the wrap (Young's modulus 3.4 GPa). This HAY demonstrated a Poisson's ratio as low as −2.7 for the yarn with 13° wrap angle [18]. Miller et al. fabricated a HAY using polyurethane fibre as core (Young's modulus 53 MPa) and ultra-high molecular weight polyethylene fibre as wrap (Young's modulus 6 GPa) and obtained a Poisson's ratio of −2.1 [10]. Miller et al. fabricated the HAY using nylon fibre as the core (Young's modulus 1.6 GPa) and carbon fibre as the wrap (Young's modulus 143 GPa) which demonstrated Poisson's ratios of −5.8, −2.3 and −1.1 for 10°, 20° and 30° wrap angles [11] respectively.

In this paper we explore the effect of core-indentation effects on the auxeticity of the HAY by investigating a range of HAYs with various core moduli but the same wrap modulus and examining the resultant cross-sectional deformation of core and wrap.

2. Experimental methods

Six types of HAYs were fabricated for core-indentation effect studies and subsequently named as yarns A, B, C, D, E and F. Helical auxetic yarns were manufactured using a bespoke spinner mechanism as described earlier [18]. Approximately 10 m of yarn were fabricated for each HAY type. According to previous works [17–19], the lower initial wrap angle of the HAY offers better auxetic performance. Therefore, a low initial wrap angle of approximately 12° was maintained for all HAYs in this work.

The yarn components and the material properties of the component fibres are summarised in Table 1. Mechanical testing of fibre and yarn samples were carried out according to ASTM D3822-07 – tensile properties of single textile fibres [23].

2.1. Sample preparation for cross section analysis of the HAY

The cross section analysis was carried out under optical microscope in order to investigate the core indentation effect of the HAY. A 70 mm length of each HAY was inserted through a glass pipette and the setup was mounted in a Lloyd instruments-EZ 20 tensile testing machine under one specific load. Epoxy resin was then carefully poured into the pipette and the bottom of the pipette was sealed. The epoxy was allowed to cure for a period of 12 h. The HAY under specific load was thus embedded in the resin and the yarn was frozen at the strain generated at that load. After removal of the load, the yarn retained that strain. The sample was cut in the transverse direction (normal to the applied load), polished and the cross section of the HAY was investigated under optical microscope with 60 times magnification. For the sake of convenience, this shall be referred as 'cross sectional image'. Three yarn samples were prepared for each load value, and specific loads were selected to cover the entire load range between zero load and failure point of each HAY. The applied load values are summarised in Table 2. Cross-sectional images under zero load were not considered, as the wrap and the core would become loose and lose their wrapping angle. A small amount of tension is required in order to maintain the HAY's characteristics.

2.2. Study of deformation of the core and wrap caused by the wrap in the ideal case (no core-indentation effect in the HAY)

The cross-sectional images obtained from the process described above will be used to study core indentation effect of the yarn. In order to determine the auxetic effect in the ideal case, the length of the wrap embeds into the core was measured (Fig. 1c). When this length is added to the diameter of the yarn to compensate the losing net width of the yarn due to core indentation effect, then hypothetical diameter of the yarn with no core indentation effect is obtained. Image J software was used for the length measurement. The known diameter of the core was obtained through SEM image and was used for calibration.

2.3. Determination of Poisson's ratio of the HAY

Once all the tests had been carried out, the Poisson's ratio of each HAY was determined through three separate methods: (1) Longitudinal and transverse strain was obtained by a high magnification, non-contact video system, coupled with Lloyd Instruments (www.lloyds-instruments.co.uk) EZ 20 tensile tester. Tensile measurements under displacement control were performed with a 500 N load cell at a speed of 5 mm/min. Gauge lengths were 70 mm for all yarns. Meanwhile, the images were captured at regular strain intervals by a 4.9 MP digital camera (Edmund Optics EO-5012C USB). For the sake of convenience these images shall be referred as 'external images'; (2) Transverse strain obtained from the cross sectional images that were processed by the method in Section 2.1, and longitudinal strain obtained from the external images under the same load; (3) Transverse strain of the hypothetical yarn with no core-indentation effect at a specific load was determined using the modified cross-sectional images through the method in Section 2.2, and longitudinal strain was obtained from the external images at the same load. Thus the