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Parametric sensitivity analysis to maximise auxetic effect of polymeric fibre based helical yarn

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ABSTRACT

Studies on designing polymeric fibres based helical auxetic yarn (HAY) to maximise their auxetic effect are yet to propose optimised design configurations for general impact mitigation applications. This study therefore presents optimal design parameters through analytical calculations and finite element (FE) method. Three main design parameters were considered which includes Poisson's ratio, core/wrap diameter ratio, and starting wrap angle. The Poisson's ratio of the HAY was calculated by measuring its total diameter at a given rate of strain. The investigation found here to be a starting wrap angle of a HAY (critical angle) that resulted in the highest possible exhibiting of the auxetic effect. The critical angle was determined to be 7°, and a maximum NPR of −12.04 was achieved with this design.

1. Introduction

It has been suggested that helical auxetic yarn (HAY) can be woven into technical auxetic textiles and placed in a composite for body armour and blast mitigation applications [1]. A material that is auxetic exhibits a negative Poisson's ratio (NPR). This means that the cross-section of the material will become larger when a tensile force is applied in the transverse direction, and smaller when a compressive force is applied in the transverse direction. The opposite is true in conventional materials [2]. Auxetic materials have been found to possess a range of unconventional mechanical properties. These include increased indentation hardness [3], fracture toughness [4], strain energy dissipation [5], and shear toughness [6,7]. These unusual properties make auxetic structure ideal for use in many applications in many different disciplines, including defence, fashion, medicine and sport [8–10].

The helical auxetic yarn (HAY) presented itself as the most fitting structure to be chosen for the study; as well as having the greatest potential to maximise the auxetic effect [11–19]. The HAY has been shown to be capable of achieving a NPR of −6.8 [17], which is the highest published value of any auxetic material to date. An array of HAYs that make up a fabric sheet all exhibiting a NPR would amplify the auxetic effect, thus increasing the desirable enhanced mechanical characteristics. Work published by previous authors up to now, has identified key parameters involved in manipulating the behaviour of the HAY, such as the starting wrap angle [13–15,17], tensile moduli of component materials [13,15–17], and fibre diameter sizes [13,14]. However, contradictory claims made by various authors as to which design configuration increases the auxetic effect have made it evident that further investigation is required to determine the optimal design parameters. Whilst previous studies have shown that lowering the starting wrap angle tends to result in a higher maximum NPR [13,14,17]; none have identified at which angle that assumption becomes untrue. This study aims to determine the optimal design configuration for maximising the auxetic effect by finding the starting wrap angle which results in the greatest NPR using finite element analysis (FEA). The scope of the study was extended to investigate the effect of changing core and wrap diameter sizes through FEA.

Papers published on HAYs since they were first designed by Hook [7] have studied the design characteristics of the structure and focused on identifying the defining factors that contribute to the auxetic behaviour in the material [13–17]. This has been done mainly through simulated or experimental tensile testing; or by comparisons of both tests. The structure of the HAY can be defined by various geometrical parameters that all have an effect on its auxeticity to varying degrees. These were the factors considered in the modelling of the yarn. The factors are: wrap diameter, core diameter and starting wrap angle [13]. The material properties that affect a HAY's performance are: Young's modulus of both core and wrap; and Poisson's ratio of core and wrap. Various studies of HAYs

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Nomenclature

NPR	negative Poisson's ratio	d_c	core diameter (μm)
FEA	finite element analysis	d_w	wrap diameter (μm)
HAY	helical auxetic yarn	d_{c0}	initial core diameter (μm)
Θ	wrap angle (°)	d_{w0}	initial wrap diameter (μm)
υ_{xy}	Poisson's ratio of yarn	ε_x	longitudinal engineering strain
L	length of yarn (mm)	ε_y	contractile engineering strain
L_{c0}	initial core length (mm)		
L_{w0}	initial wrap length (mm)		

[11,12,15] showed that the wrap angle has a profound effect on the NPR value. For example, different values for NPR obtained by Miller et al. [11] based on three different HAY designs. The lowest wrap angle of 10° resulted in the largest NPR value of −5.8, indicating that a low starting wrap angle is desired for maximising the auxetic behaviour of the HAY. The results of Sloan et al. [15] study generally agreed with these findings. The HAY with the lowest angle of 13° achieved a maximum NPR of around −2.5. The HAYs with wrap angles of 30° and 38° did not ever have a negative Poisson's ratio when put in tension. This revealed that the influence of the starting angle of the wrap on NPR is so prominent, that an angle too large will prevent the auxetic effect from taking place at all [15].

Wright et al. [14] observed that the selection of boundary conditions at the end of the yarn have a minimal effect on the yarn behaviour after 10 cycles. A model made up of 10 cycles displayed results within 1.5% accuracy of a model of 50 cycles – showing that the end effects did not have a profound effect on result accuracy at that many cycles. The findings indicated that designing of the HAY model did not require an excessive number of cycles. Wright et al. [14] also claimed that the stiffness of the fibre components were the major influences on the performance of the HAY. They alleged that a HAY with a low stiffness ratio is not fit-for-purpose, and it was shown that a lower core/wrap diameter ratio results in a higher NPR value. The study also highlighted the effect that increasing the Young's modulus of the wrap had on the NPR value. Study by Sibil and Rawan [13] claimed that by increasing the core/wrap diameter ratio – and therefore lowering the stiffness ratio – the value of NPR can be increased. They showed that a HAY with a stiffness ratio of 0.003 (achieved by virtually reducing the wrap diameter by three orders of magnitude) displayed a higher magnitude of NPR when compared to a HAY with a stiffness ratio of 7.4. These contrasting results made it difficult to predict the ideal design parameters the HAY should have had, but elucidated the need for further study to determine the ideal design configuration to maximise the auxetic effect. To further develop the design of the HAY, it was important to identify the optimum configuration of core and wrap that this previous work had not shown. However, both studies showed that the core/wrap diameter ratio is inversely proportional to the core/wrap stiffness ratio.

For the arrangement of wrap and core to work as intended; the wrap should be composed of material with a relatively high Young's modulus, and the core should be composed of material with a Young's modulus lower than that of its wrap counterpart [18]. It is also important to note that the behaviour of HAY fabrics is heavily affected by the inter-yarn contact friction and shear, and in single HAYs this is compounded by the friction and contact between the core and the wrap. However, in this study, the model does not consider contact friction between the core and the wrap, and therefore, the purpose of this study is to optimise the design features of the auxetic behaviour under deformation mechanisms and enhanced properties because of having a negative Poisson's ratio.

2. Methodology

The model in this study was analysed under the axial tensile load test conditions. The tensile testing method is the only procedure to date, that has been used to determine the NPR of a HAY [11–19]. The load was applied until a maximum deformation of 1 mm per cycle of HAY had been reached [17], and the model does not consider contact friction between the core and the wrap.

2.1. Poisson's ratio

To discover how prominent, the effect of changing the component Poisson's ratios of the HAY, a sensitivity test was carried out. This would involve the comparison of NPR values achieved by the HAY used in Sibal and Rawan's study [13], with a new design. As previously mentioned, the study assumed a Poisson's ratio value of 0.3 for both core and wrap components. These components were made of *nylon* and *carbon fibre*, respectively. However, the real Poisson's ratio for these materials can be sourced from data sheets or manufacturers. A data sheet provided by DuPont confirmed that the Poisson's ratio for nylon 66 is 0.4 [20]. These values were selected as the material properties for the new design of HAY. The remaining input parameters of each model, i.e. Young's modulus, component diameter and wrap angle, are shown in Table 1 (*sensitivity test*). The reason for changing only component Poisson's ratio values was to confirm from the test that a different NPR would be attributed to Poisson's ratio, and prove the new model results to be more authentic.

2.2. Wrap diameter

Sibal and Rawan's study [13] attempted to prove that a greater core/wrap diameter ratio increases the auxetic effect, but Wright et al. [14] study contradicts their results, by claiming the opposite to be true. These inconclusive results indicated that further investigation was required to verify which of those claims were correct. To do so, models with varied core and wrap diameters were designed and analysed. Using a base model with the same parameters as Model A2 from the previous section, variant designs were produced for the test. Model A2 was used as the base design for this test because the material properties of that model were a better representation of the component materials than Model A1. The variant models' input parameters are shown in Table 1 (section 2: core-to-wrap diameter ratios).

The first variant, Model B1, was designed with a new core diameter of 600 μm (as used in the Wright et al. [14] study). All other parameters remained unchanged so that the results would prove that a change in NPR was due to the reduced core diameter. To further investigate the effect of changing diameter size, a second variant, B2 was designed. This model had an increased diameter, proportional to the size difference in B1. This was done so that a trend in behaviour of the HAYs can be attributed to changing the