DEVELOPMENT AND CHARACTERIZATION OF HIGH PERFORMANCE AUXETIC FABRICS PRODUCED USING PURL KNITTED STRUCTURES

Rui Magalhães[1,a*], Clara Gonçalves[2,b], Sohel Rana[3,c], Raul Fangueiro[4,d], Pedro Nunes[5,e] and Gustavo Dias[6,f]

[1,3] Centre for Textile Science and Technology (2C2T), University of Minho, Guimarães, Portugal

[4]Department of Mechanical Engineering, University of Minho, Guimarães, Portugal

[2,5,6] Institute for Polymers and Composites (IPC), University of Minho, Guimarães, Portugal

[a]ruimagalhaes@fibrenamics.com, [b]claragonçalves@fibrenamics.com, [c]sohelrana@fibrenamics.com, [d]rfangueiro@dem.uminho.pt, [e]jpn@dep.uminho.pt, [f]grdias@dep.uminho.pt

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Abstract. This paper reports an overview of auxetic fibrous structures with negative Poisson´s ratio (NPR). These type of behaviour have a vast potential for applications in personal protection due to their high energy absorption and excellent impact resistance. The aim of this study, is to evaluate the behaviour of purl structure design, produced through weft knitting technology using high performance polyamide (PA) fibres. Fabric structural parameters (e.g. loop length) and machine parameters (e.g. take down load) were varied in order to investigate their influence on the behaviour of the produced fibres structures and their composites. Overall, all the auxetic fabrics and composites showed a superior strength and energy absorption capability as compared to their non-auxetic counterparts.

Introduction

The number of publications dealing with multifunctional materials and structures has been increase along the years. One part of this materials is the advanced fibrous structures and their composites who are the new silicon welfares, used in different fields includes medicine, military, architecture, technology, transportation, civil engineering etc.[1]–[5]

The term auxetic originates from the greek word ("*auxetikos*") which means "that which tend to increase" or "auxetos" meaning "capable of growing". Auxetic materials are a singular class of materials having a negative Poisson´s ratio (NPR), i.e. stretching of these materials in longitudinal direction results in widening in the transverse direction.

The theoretical limits of the Poisson ratio (ν) for isotropic materials are between (-1) and (0.5), being the positive values the most usual, reflecting the conventional materials.

Nowadays, auxetic materials are very attractive to the scientific community due to their interesting properties such as enhanced strength, better acoustic behaviour, improved fracture toughness, superior energy absorption, damping improvement and indentation resistance. This property can be qualitatively explained by the relation among the shear modulus (G) (or rigidity), the Young´s modulus (E), bulk modulus (K) and the Poisson´s ratio (ν). The shear-to-bulk (G/K) stiffness ratio is higher when we have Poisson ratio with negative values, see expression (1).[6], [7]

$$\frac{G}{k} = \frac{3}{2}\frac{1-2\upsilon}{1+\upsilon} \qquad (1)$$

This behaviour is recommended for wide range of applications including apparel textiles (functional fibres), technical fibrous structures (air filter, shock absorber, sound absorber etc.), materials for personal protection (helmets, rigid plates, protective clothing, pads, gloves), bio-medical industry (wound pressure pad, artificial blood vessel), in sensors and actuators (hydrophene, piezoelectric devices), etc. [8]–[12]

To this point, only a limited research has been developed on auxetic fibrous structures and composite materials produced from these structures. In bridge these knowledge gap, the principal objective of the publish work is to develop a novel weft knitted auxetic fibrous structure, using high performance yarns, as material, and study the influence in the Poisson´s ratio. Also, these fibrous structures have been impregnated with thermosetting resin, and the auxetic behaviour of the developed composites was characterized.

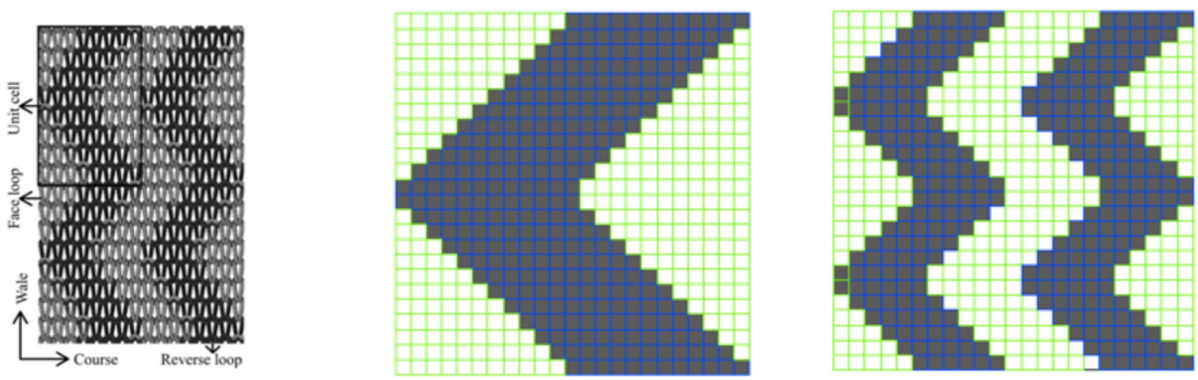
Materials and Methods

1. Production of Plain knit and auxetic fibrous structures

Different types of fibrous structures were developed based on re-entrant structure designs. A modern fibre placement technique, flatbed knitting machine, was used to produce these structures and can be seen in Fig. 1. This flatbed knitting machine has gauge of 10 needles/inch and two benches with a full working of 127 cm.

Fig. 1. Flatbed knitting machine STOLL CMS 320 TC

The pattern used was based on a purl structure, see Fig. 2, through zigzag arrangement of the face and reverse loops. The knit pattern was in planar form and after production it tend to curl and form a three-dimensional geometry.



a) b) c)

Fig. 2. Pattern diagram; a) Scheme b) Unit cell of Purl structure produced c) Unit cell of Modified Purl Structure

Plain jersey knitted fibrous structures, without auxetic design, were also produced using the same parameters, in order to compare their behaviour. The parameters used to produce the plain knits and the auxetic fibrous structures are listed in Table 1.

Table 1 Parameters used to produce plain knit and auxetic fibrous structures

Parameters	**Plain knit**	**Auxetic Structure 1**	**Auxetic Structure 2**
Material	Polyamide HT	Polyamide HT	Polyamide HT
Auxetic Design	-	Purl Structure	Modified Purl Structure
Linear density (tex)	97	97	97

No. of yarns	1	1	1
Loop length*	11	11	11
Take down load*	8	8	8

*in machine units

Fibrous structures parameters (e.g. loop length) and machine parameters (e.g. take down load) were also varied in the production process and they are listed in (Table 2). The parameters were changed in order to study their influence on the Poisson´s ratio. For this analysis only the modified purl structure was considered.

Table 2 Variation of Parameters in the fibrous structures produced

Sample name	Auxetic Structure 2.1	Auxetic Structure 2.2	Auxetic Structure 2.3	Auxetic Structure 2.4
Linear density (tex)	97	97	97	97
No. of yarns	1	1	1	1
Loop length*	12	10	11	11
Take down load*	8	8	9	7

*in machine units

2. Production of Composite Materials

The produced fibrous structure was subsequently impregnated with thermoset resin. The matrix used to produce composites specimens was an epoxy resin, and the composite materials produced are listed in Table 3. For all specimens, one layer of fabric was used and the average resin weight was approximately 50%.

Table 3. Details of composite Specimens

Name	**Material**	**Fibrous strucutre**
Plain Composite	Polyamide HT	Plain knit
Composite Auxetic 1	Polyamide HT	Auxetic Structure 2

3. Characterization of Physical Properties

In order to quantity the thickness of the fibrous structures produced NP EN ISO 5084:1999 Textiles (Determination of the thickness of textile and textiles products) standard was used. The area of the fabrics was measured through image analysis using ImageJ software. These technique was used because when was divide the fibrous structures in samples, some yarns can be removed and the marked area can be different then the real area.

4. Characterization of Poisson´s ratio

The measurement of the displacements in the structure was carried out using a digital image correlation (DIC) technique. MatLab® code was created to analyse the video (with 3840x2160 resolution and frame rate of 24 images/second) recorded from the tensile test. This program ensures the measurement of the longitudinal and transverse elongations and calculate the Poisson's Ratio (PR) to provide a result in form of graphic.

5. Characterization of Mechanical behaviour

The objective of the mechanical behaviour investigation was determinate the loading, elongation up to the breaking material and the energy absorption. The mechanical characteristic of textile fabric followed a methodology described in the standard (ISO 13934-2: Textile – Tensile properties of fabrics – Part 2 Determination of maximum force using the grab method). According to above standard, the dimensions was performed at a constant speed of 5 mm/min until the rupture (see Fig. 3).

The composites specimens were testing according to the methodology described in the standard (Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials).

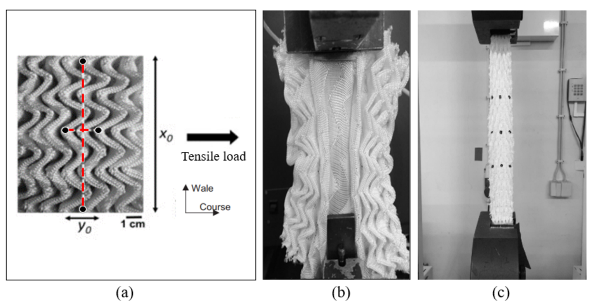


Fig. 3 Tensile testing setup; a) distance between marked points on the knitted fibrous structure, b) fibrous structure, c) composite material

Composites specimens were also subjected to drop weight impact testing to evaluate their impact behaviour, which were preformed using (Fractiovis Plus®) drop weight impact testing equipment from Ceast, in accordance to the ASTM D7136/D7136M standard. Hemispheric impactor having 20 mm diameter and a mass of 10.044 kg was used. By falling from a height of 500 mm, it impacts the sample at the speed of 3.13 ms^{-1}.

Experimental Results and Discussion

1. Poisson´s ratio

Analysing different fibrous structures, the Poisson´s ratio shows different values when was changed the loop length and the take down load (see Table 4). According to the results, the higher NPR was shown in the fibrous structure produced with a loop length of (11) and the take down load of (8).

The loop length had a strong influence on the auxetic behaviour. In the wale and course direction, increasing the loop length led to increase the negative value of PR. The average of PR with the same auxetic design, modified purl structure, with a loop length of 12, 11 and 10, was respectively -0.19, -0.03 and 0.07.

Analysing the composite materials behaviour in terms of PR, the composite auxetic structure 1, obtained negative values for the PR which showing an auxetic behaviour. These value decrease, comparing with the Auxetic Strucutre 2, being an expected result because the composite material was more rigid due to the polymeric matrix.

Table 4. Maximum values of NPR of different fibres structures and composites

Name	**Thickness**	**NPR**	
		Wale direction	**Courses direction**
Plain structure	0.88 (2)[a]	-	-
Auxetic Structure 1	18.11 (8)	-0.06	-0.44
Auxetic Structure 2	10.45(4)	-0.15	-0.60
Auxetic Structure 2.1	14.77 (1)	-0.21	-0.07
Auxetic Structure 2.2	10.20 (3)	-0,01	-0,01
Auxetic Structure 2.3	13.67 (1)	-0.39	-0.11
Auxetic Structure 2.4	12.50 (1)	-0.09	-
Plain composite	1.57 (12)	-	-
Composite Auxetic structure 1	15.10 (3)	-0.10	-0.45

[a]The values of coefficient of variation are given between parentheses

2. Mechanical behaviour

The mechanical properties obtained on the fibrous structures and composites materials are listed in Table 5. It is clear that, the auxetic fibrous structures exhibited superior maximum force, elongation as well as energy absorption than conventional fibrous structures. This indicates the positive influence of the auxetic design in improving the mechanical performance of fibrous structures. The value obtained for the energy absorption increase 48% and the maximum force increase 13.5%, when was used fibrous structures with the auxetic behaviour. When was compared composite materials, we can see an increase of the mechanical properties in the case of composite with auxetic behaviour, 122% in terms of maximum force and 150.1% in energy absorption. Regarding to the impact test, was also possible to obtain the values of energy absorption. This test was only performed in the case of composite material because in case of fibrous structure the perforation didn't occur. For the testing purpose, the composite produce without auxetic behaviour shows a lower peak force but the energy absorption is higher 107% in the case of composite with auxetic behaviour.

Table 5. Mechanical testing results of fibrous structures and composites

Name	Areal density (g/m^2)	Tensile behaviour			Impact	
		Maximum Force (N)	Elongation at Maximum Force (mm)	Energy absorptio n (kN.mm	Peak Force (N)	Absorbed energy (J)
Plain strucutre	1.68 (15)	1304.0 (6)[a]	104.7 (8)	30.3 (*)	-	-
Auxetic Structure 2	15.09 (3)	1480.5 (*)	169.4 (*)	44.9 (*)	-	-
Plain composite	4.04 (5)	758.6 (6)	224.8 (4)	68.3 (8)	1241 (7)	22.54 (16)
Auxetic Composite 2	25.67 (4)	1689.0 (9)	191.0 (*)	170.8 (12)	1156 (6)	46.7(*)

[a]The values of coefficient of variation are given between parentheses

*CV ≥ 20

Conclusion

In this paper, auxetic fibrous structures using knitting technology has been developed using high performance yarns such as high tenacity PA. The experimental results of the fibrous structures show NPR and were strongly influenced by the structural parameters as well as machine parameters.

Therefore, considering the NPR and tensile strength, it can be concluded that PA fibrous structures, with the take down load of 8 and loop length of 11 can provide the balanced auxetic as well as tensile properties and will be suitable for wide range of applications for example, in personal protection such cut resistance fabrics, bullet proof vest, helmets, etc.

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