Novel high performance auxetic fibrous structures for composite reinforcement

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Abstract. This paper reports the development of novel auxetic fibrous structures from high performance yarns using knitting technology for application as reinforcement in composites. Two types of high performance yarns, namely, para-aramid (p-AR) and polyamide 6.6 (PA), were used to produce three distinct auxetic structures: purl, re-entrant lozenge and re-entrant star structures. It was observed that all structures produced could achieve maximum negative Poisson’s ratios (NPR) of -0.60, -0.54 and -0.47 in the course direction of purl and lozenge and in wale direction of star structures, respectively. The auxetic textile structures also presented better tensile strength and energy absorption (except re-entrant lozenge structure) than plain knitted textiles produced by using the same type of fibres and parameters.

1. Introduction
In recent years, the use of textile technology to fabricate auxetic materials has attracted more and more attention due to their superior fracture toughness and impact and indentation resistance, besides other interesting characteristics [1,2]. Auxetic reinforcements are now used in composite materials to improve the properties that are desired to achieve, for example, in crash helmets, sport clothing, sponges, ropes, filtration and other shock absorbing products. They are also used in the biomedical, automotive and defence industries [3,4].

Several studies revealed that auxetic effect can be achieved by developing structures that involve the rotation of units such as squares, rectangles, triangles, rhombi and parallelograms [5,6]. The auxetic fabric structures were manufactured by using specially designed fibrous arrangements that were thoroughly investigated. The present study evaluates the auxetic behaviour of NPR weft-knitted fabrics made from PA and p-AR fibres and polymeric matrix composites using them as reinforcing layers. Wherein an epoxy resin has been selected as matrix due to its excellent toughness, adhesion, thermal and chemical resistance [2].
2. Experimental work

2.1. Materials
Knitted fabrics were produced from p-AR fibre yarns Standard Twaron and high-tenacity PA fibre yarns, supplied by Teijin Company (Arnhem, Netherland) and Rhodia Company (Lisboa, Portugal), respectively. An epoxy resin Biresin® CR83 combined (100:30 ratio) with hardener Biresin® CH83-2, both from Sika Deutschland GmbH/Germany, were used as matrix of the composites produced in this work.

2.2. Production of fibrous structures and their composites
In order to compare the behaviour of auxetic structures with non-auxetic ones, jersey plain knitted fabrics were also produced using the same parameters and the schematic geometries provided in Figure 1. Weft-knitted textile structures were manufactured on a 10-gauge Stoll CMS 320 TC flat knitting machine (Stoll GmbH & Co., Reutlingen, Germany). Weft-knitting refers to the knitting direction: the stitches are knitted successively in the weft direction, also called course direction, and the loops are interconnected in the wale direction.

![Schematic geometries regarding high performance fibrous structures produced using knitting technology: a) Jersey plain, b) purl (Aux 1), c) re-entrant lozenge (Aux 2) and d) re-entrant star (Aux 3.1, 3.2).](image)

Table 1. Parameters used to produce jersey plain and auxetic knitted fabrics.

| Knitted fabric | Fibre type | Linear density (Tex) | No. of yarns | Loop length* | Take down load* |
|----------------|------------|----------------------|--------------|--------------|----------------|
| Jersey plain   | Polyamide  | 97                   |              |              |                |
| Aux 1          | Polyamide  | 97                   |              |              |                |
| Aux 2          | Polyamide  | 97                   | 1            | 11           | 8              |
| Aux 3.1        | Polyamide  | 97                   |              |              |                |
| Aux 3.2        | Para-aramid| 172                  |              |              |                |

* in machine units

The produced fabric structures were subsequently impregnated with an epoxy resin by using the vacuum infusion technique. One layer of fabric was used and the average weight gain after resin impregnation was approximately 50% for all composites specimens.
2.3. Auxetic, physical and mechanical properties
In this work, the digital image correlation (DIC) method was used to determine the Poisson’s ratio and, therefore, to assess the auxetic behaviour of the developed textile structures.

The measurement setup was fixed to a universal mechanical testing machine (see Figure 2) in which the structures were vertically subjected to tensile tests after being attached to the clamps of the equipment with regard to measure their displacements in course and wale directions. The specimens were marked at specific points in both directions, as shown in Figure 2. Images taken from fabrics and composites under tensile deformation were recorded, analysed and treated by using the MatLab® high-performance software for assessing their Poisson’s ratio. The image recording was performed using 3840x2160 pixels and a frame rate of 24 images/second.

\[ \varepsilon_x = \frac{x_n - x_0}{x_0} \]  
\[ \varepsilon_y = \frac{y_n - y_0}{y_0} \]

Figure 2. A schematic diagram and photograph of the tensile testing system Poisson’s ratio measurement: (a, b) setup of testing and (c) image processing steps.

Then, the course and wale strains in the specimens were determined using the following equations:

Where \( x_n \) and \( y_n \) are the distances between the points marked in the wale and course directions, respectively, in each deformation step, i.e., 1 cm. \( x_0 \) and \( y_0 \) are the initial intervals (first frame) between the reference points. The Poisson’s ratio was then calculated through the relation between the deformation in the wale and course directions in each deformation step. It can be seen these deformations in a schematic representation shown in Figure 3a.

The tensile tests were also used to determine the tensile strength, strain and energy absorption until failure in the developed fabrics and composites. The tests on fabrics were performed according to the standard ISO 13934-2 Textiles (Tensile properties of fabrics – Part 2 Determination of maximum force using the grab method), in an universal testing machine, Hounsfield H 100 KS with a load cell of 10 kN. Whereas, the mechanical properties of the composites were made according to the ASTM D3039/D3039M-00 standard (Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials) in the same machine at constant crosshead displacement rate of 5 mm min\(^{-1}\), with a 2.5 kN load cell but using different clamps, (see Figure 3 c). In both cases, five specimens of each configuration were tested.
Figure 3. Tensile testing setup of (a) distance between the marked points on the knitted fabrics (b) knitted fabrics and (c) composite materials.

To assess the impact behaviour of the developed composites, their specimens were also subjected to drop weight impact testing accordingly to the ASTM D7136/D7136M standard in a *Fractovis Plus®* drop weight impact testing equipment from Ceast. An hemispheric impactor having 20 mm diameter and a mass of 10.044 kg was made to fall from a height of 500 mm in order to impact the sample at the speed of 3.13 ms⁻¹.

The thickness of the knitted fabrics and their composites were measured using NP EN ISO 5084:1999 Textiles (Determination of the thickness of textile and textile products) standard.

3. Experimental results and discussion

3.1. Mechanical behaviour of the knitted fabrics

The results of thickness, areal density and NPR measurement of the fabrics produced are listed in Table 2.

| Knitted fabric | Thickness (mm) | Areal density (g/m²) | Maximum NPR values Wale | Course |
|---------------|----------------|---------------------|-------------------------|--------|
| Jersey plain  | 0.88 (2)       | 2.46 (3)            | -                       | -      |
| Aux 1         | 10.45 (1)      | 14.24 (4)           | -0.15                   | -0.60  |
| Aux 2         | 7.38 (4)       | 5.98 (5)            | -0.23                   | -0.54  |
| Aux 3.1       | 10.48 (2)      | 8.96 (2)            | -0.47                   | -0.32  |
| Aux 3.2       | 13.90 (4)      | 14.54 (7)           | -0.08                   | -0.29  |

*The values of coefficient of variation are given between parentheses*

It may be observed that the auxetic fabrics exhibited much higher thickness and areal density as compared to the jersey plain one made using the same parameters. Aux 3.2 had also more thickness and areal density than all the other auxetic structures made from PA fibre yarns due to the higher linear density of p-AR fibres. Furthermore, the p-AR yarn fabrics presented much lower NPR than those produced from the PA yarns. This could be due to the higher flexibility of the PA fibre yarns, which may result in better structural rearrangement under tensile loading leading to superior auxetic behaviour.
Almost all auxetic fabrics exhibited maximum NPR value in the course direction. The exception was the Aux 3.1 knitted fabric which present a maximum NPR of -0.47 in wale direction.

The mechanical properties determined on the fabric structures produced are listed in Table 3. It is clear that in general the auxetic fabrics exhibited superior maximum force, elongation as well as energy absorption than conventional fabrics (except Aux 2). This indicates the positive influence of the auxetic design in improving the performance of fabric structures.

| Knitted fabric | Maximum Force (N) | Elongation at Maximum Force (mm) | Energy absorption (kN.mm) |
|----------------|-------------------|---------------------------------|--------------------------|
| Jersey Plain   | 1304.0 (6)a       | 104.7 (8)                       | 30.3 (22)                |
| Aux 1          | 1480.5 (*)        | 169.4 (*)                       | 44.9 (37)                |
| Aux 2          | 1070.0 (19)       | 140.98 (*)                      | 22.4 (19)                |
| Aux 3.1        | 1465.5 (10)       | 177.4 (7)                       | 41.9 (14)                |
| Aux 3.2        | 1610.0 (10)       | 234.0 (2)                       | 68.0 (17)                |

* The values of the coefficient of variation (CV) values are given between parentheses
* CV ≥ 20

3.2. Behaviour of knitted fabric reinforced composites

The results of thickness, areal density and NPR measurement of the composites are listed in Table 4. It is expected that this study could help us understanding the deformation mechanism of auxetic composites under axial tension load.

| Composites   | Thickness (mm) | Areal density (g/m²) | Maximum NPR Wale | Maximum NPR Course |
|--------------|----------------|----------------------|------------------|--------------------|
| Jersey plain | 1.57 (12)a     | 4.04 (5)             | -                | -                  |
| Aux 1        | 15.10 (3)      | 25.67 (4)            | -b               | -0.1               |
| Aux 2        | 9.70 (9)       | 9.26 (10)            | -0.35            | -0.1               |
| Aux 3.1      | 14.20 (6)      | 13.80 (11)           | -0.17            | -0.05              |
| Aux 3.2      | 13.25 (7)      | 19.77 (8)            | -0.10            | -0.20              |

* The values of the coefficients of variation are given between parentheses
* Clamp slippage before fabric reinforced composite break

The same trends were also observed for the composites produced from the auxetic fabrics, which presented much higher thickness and areal density than the conventional ones made from jersey plain fabrics. This was caused by the different arrangement of the knitted loops in the auxetic structures, which increase the thickness and mass per unit area not only of the fabrics themselves but also of their reinforced composites.

Anyway, the auxetic composites showed lower NPRs than their predecessor fabrics. This might be explained by the much higher restriction to movements and rearrangements of the composites, resulting from the addition of a solid, continuous and stiffer epoxy matrix, which strongly contributed for the reduction of their lateral expansion. It may be also seen that composites and their prior fabrics seemed to present maximum NPR values in the same direction (course and wale directions). Aux. 2 was the only exception but that seemed to be caused by the slippage at clamps that happened in the tensile tests made in the course direction.
Also like their previous fabrics, composites reinforced with p-AR fabrics had lower NPR than those produced with PA ones. The highest NPR values obtained in the composites were -0.35 and -0.2, in wale and course directions, respectively.

As it may be seen in Table 5, the composites made from auxetic fabrics demonstrated to absorb higher energy than those from non-auxetic ones (jersey plain). While the p-AR (Aux 3.2) and polyamide (Aux 3.1) auxetic knitted fabrics showed to withstand very a similar load (see Table 3), the composite derived from the p-AR (Aux 3.2) has shown to resisted to a much higher load and presented a considerable lower elongation than the composites based on both polyamide auxetic and jersey plain fabrics. Hence, it may be concluded that the material of the fibre reinforcement seemed to play more important role on the mechanical properties obtained in the final composites produced from the auxetic knitted fabrics.

### Table 5. Mechanical testing results of knit fabric reinforced composites

| Composites   | Maximum force (N) | Elongation at maximum force (mm) | Energy absorption (kN.mm) |
|--------------|-------------------|----------------------------------|--------------------------|
| Jersey plain | 758.6 (6)         | 224.8 (4)                        | 68.3 (8)                 |
| Aux 1        | 1689.0 (9)        | 191.0 (*)                        | 170.8 (12)               |
| Aux 2        | 1125.4 (3)        | 113.9 (3)                        | 60.3 (8)                 |
| Aux 3.1      | 699.2 (8)         | 278.2 (5)                        | 87.0 (9)                 |
| Aux 3.2      | 2681.5 (8)        | 51.0 (18)                        | 78.7 (14)               |

* The values of the coefficients of variation (CV) are given between parentheses
* CV ≥ 20

Figure 4 depicts the representative energy–time–force curves obtained from the low-velocity impact tests made on non-auxetic and auxetic textile composites using an impact energy of 49.2 J. Among the four different structures tested, the non-auxetic presented the highest peak force which is 1035 N, while auxetic textile composite exhibited slightly lower peak force under the same impact energy. The peak force for Aux 1, 2, 3.1 and 3.2 composites were 805 N, 711 N, 856 and 995 N, respectively. Moreover, the impact duration for the non-auxetic and auxetics Aux 1, 2, 3.1 and 3.2 textile composites were 14, 25, 13, 14 and 10 ms, respectively. Despite the slightly higher peak force presented by the non-auxetic composite, the auxetic textile composites exhibited greater absorption of energy (34.8 J for Aux 1) and better force reduction than the non-auxetic under low-velocity impact at the energy of 49.2 J, which seems to indicated that the auxetic textile composites may have superior impact protective performance than the non-auxetic one.

It may be also seen that the impact energy absorption of all knitted fabric reinforced composites can be divided into three distinct stages. In the first stage, the value of absorbed energy is relatively low due to small deformation of the matrix and insignificant compression of textile structure. In a second stage, the energy–time curve increases rapidly and reaches the peak value ($E_{\text{max}}$), representing the deformation of the reinforced auxetic textile structure and the increase in vertical displacement of the composite structure. At the last stage (from $E_{\text{max}}$ to the end), the absorbed energy gradually decreases until the impact process finishes.
Figure 4. Low velocity impact behaviour of the five composite materials configurations tested (Jersey plain, Aux 1, 2, 3.1 and 3.2) with the peak force ($P_{\text{max}}$) and impact energy ($E_{\text{max}}$) average.

4. Conclusions
In the present research, all fabrics and composites produced using the developed auxetic knitted yarn structures exhibited negative Poisson’s ratio (NPR) whose value, however, was strongly dependent on the type of structure (i.e., fabric configuration or composite) as well as on type of fibre yarns used. The maxima NPR values obtained were 0.47 -0.60 in the wale and course directions in auxetic knitted fabrics, respectively, and -0.35 and -0.20 in wale and course directions of their composites, respectively. The auxetic knitted fabrics themselves and their composites exhibited higher thickness, areal density, elongation and resistance under tensile loads as well as energy absorption than non-auxetic jersey plain knitted fabrics and its composite. The auxetic composites reinforced with p-AR knitted fabrics was the one that was able to support higher tensile load. Under stretching, the composites reinforced with auxetic knitted fabric also proven to present better energy absorption capability than the composite reinforced with the non-auxetic structures. However, under impact test, the difference in mechanical behaviour
between the auxetic and non-auxetic textile composites diminished probably due to reduction in negative Poisson’s ratio effect that was verified in the auxetic composites relatively to the knitted fabrics used in their production. To better optimise the design of the auxetic structures and enhance the impact performance of the auxetic composites further theoretical study is required to better understand the mechanical behaviour of the composites under low-velocity impact.

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