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Development and Characterization of Re-Entrant Auxetic Fibrous Structures for Application in Ballistic Composites

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***Abstract*—**Auxetic fibrous structures and composites with negative Poisson's ratio (NPR) have huge potential for application in ballistic protection due to their high energy absorption and excellent impact resistance. In the present research, re-entrant lozenge auxetic fibrous structures were produced through weft knitting technology using high performance polyamide and para-aramid 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 auxetic behaviours of the produced structures. These auxetic structures were then impregnated with two types of polymeric resins (epoxy and polyester) to produce composite materials, which were subsequently characterized for the auxetic behaviour. It was observed that the knitted fabrics produced using the polyamide yarns exhibited NPR over a wide deformation range, which was strongly dependant on the loop length and take down load. The polymeric composites produced from the auxetic fabrics also showed good auxetic property, which was superior in case of the polyester matrix. The experimental results suggested that these composites made from the auxetic fibrous structures can be properly designed to find potential use in the body amours for personal protection applications**.**

***Keywords*—**Auxetic fabrics, high performance, composites, impact resistance, energy absorption.

I. INTRODUCTION

AUXETIC materials possess a NPR as they expand in the transverse direction under a longitudinal tensile force and contract when subjected to a compressive force [1]. Auxetic materials show a number of interesting characteristics which make them attractive for a wide range of industrial applications [2]-[10]. Improved strength, superior impact and indentation resistance, higher shear modulus, higher energy absorption, ability to form synclastic curvature, etc. are some of the important advantages of auxetic materials [2]-[10]. These materials have been developed in almost all class of materials including metals, ceramics and polymers in different scales, macro, micro or nano. Polymer based auxetic materials offer the mechanical flexibility and ease of tailorability of structure and properties. A great deal of research attempts have been made on developing auxetic fibrous materials and textiles aiming to medical, filtration, personal protection, and other industrial sectors [11]-[20].

Till date, different synthetic (such as nylon, polypropylene, polyester, etc.) fibres with auxetic properties have been produced [12]. Alternatively, an auxetic yarn has been produced by combining two non-auxetic fibres, one with high modulus wrapped around another one with significantly lower modulus and higher elasticity. These types of yarns, known as double helix yarns, can also be used to produce auxetic textile structures [13]. Alternatively, non-auxetic fibres or yarns can be woven or knitted into auxetic structures following different designs such as foldable structures, re-entrant hexagon, star, lozenge designs, rotating rectangles, squares, etc., chiral structures and so on [16]-[20]. A number of auxetic textile structures have been produced through this approach mainly with the fibres used in the apparel production such as cotton, polyester, wool, etc. Recently, the authors produced auxetic knitted textile materials using high performance fibres such as para-aramid (Kevlar) and high tenacity (HT) polyamide using foldable structures [8]. In the present research, a type of auxetic textile structure has been produced according to re-entrant lozenge designs using Kevlar and HT polyamide fibres and their auxetic behaviours have been studied. The influence of structural and knitting parameters on Poisson's ratio of the produced structures has been investigated. Also, these textile structures have been impregnated with an epoxy and a polyester resin and the auxetic properties of the developed composites have been characterized.

II. MATERIALS AND METHODS

A. Production of Plain Knit and Auxetic Fabrics

Different types of textile structures were produced based on the re-entrant lozenge design using two types of fibrous materials (polyamide HT and para-aramid or Kevlar), and by changing the loop length and taking down load during the knitting process. A flatbed knitting machine with a needle gauge of 10 needles/inch was used. The picture of the knitting machine used to produce the fabric structures is provided in Fig. 1.

Plain jersey knitted fabrics with non-auxetic behaviour were also produced using the same parameters as used in case of auxetic fabrics in order to compare their behaviours. Table I lists the parameters used to produce the plain knits using HT polyamide fibres (the loop length and take down load are in machine unit) and auxetic fabrics using polyamide and Kevlar

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fibres. Fig. 2 shows the schematic design and picture of plain knits and re-entrant lozenge auxetic fabrics. Also, auxetic fabrics using polyamide yarns were produced using different parameters in order to investigate their influence on the auxetic behaviour, as can be seen from Table II.

Fig. 1 Flat bed knitting machine used to produce plain knits and auxetic knitted fabrics

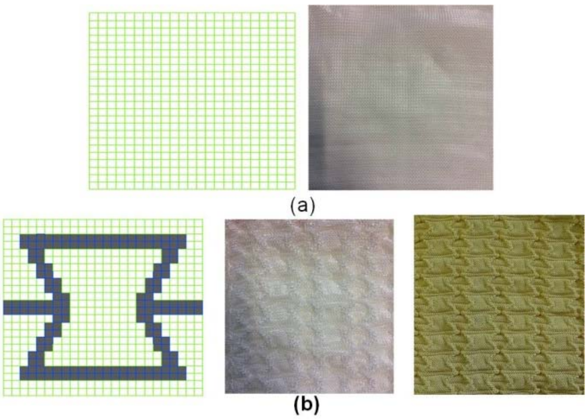

Fig. 2 Schematic design and fabrics produced using plain knit (a) and re-entrant lozenge grid designs (b)

TABLE I
PARAMETERS USED TO PRODUCE PLAIN KNIT AND AUXETIC FABRICS

Parameters	Plain knit	Auxetic Structure 1	Auxetic Structure 2
Material	Polyamide HT	Polyamide HT	Para-aramid
Linear density (tex)	97	97	172
No. of yarns	1	1	1
Loop length	11	11	11
Take down load	8	8	8

TABLE II
VARIATION OF PARAMETERS IN POLYAMIDE FIBRE MADE AUXETIC FABRICS

Sample name	Auxetic Structure 1.1	Auxetic Structure 1.2	Auxetic Structure 1.3	Auxetic Structure 1.4
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

B. Production of Composite Materials

The produced plain knits and selected auxetic structures were then impregnated with an epoxy and a polyester resin to produce composite materials. A vacuum infusion technique was used to produce the composite samples, as shown in Fig. 3. The composites were produced using only one layer of plain knit or auxetic fabrics and the resin content in the composites was approximately 50 wt.%. Three types of composite samples were prepared: (1) using polyamide plain knit, (2) using auxetic structure 1.2 and the epoxy resin and (3) using auxetic structure 1.2 with the polyester resin, as listed in Table III.

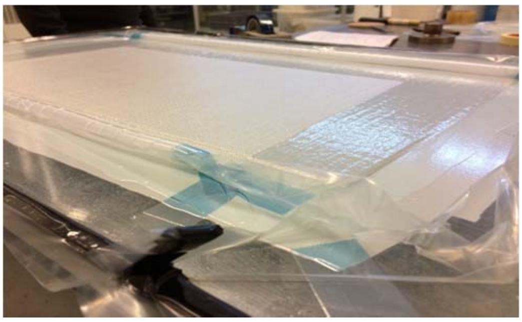

Fig. 3 Production of composite samples using vacuum infusion technique

TABLE III
COMPOSITES DEVELOPED USING PLAIN KNITS AND AUXETIC FABRICS

Name	Material	Fabrics used
Plain Composite	Polyamide HT and epoxy resin	Plain knit
Auxetic composite 1	Polyamide HT and epoxy resin	Auxetic Structure 1.2
Auxetic composite 2	Para-aramid HT and polyester resin	Auxetic Structure 1.2

C. Characterization of Physical Properties

In order to measure the thicknesses of the produced fabrics, NP EN ISO 5084:1999 Textiles (Determination of the thickness of textile and textile products) standard was used. The thickness of a fibrous structure, according to this standard, was obtained from the perpendicular distance between two reference plates, which exert a certain pressure on the fabrics (Fig. 4). During the test, the specific area of plate used was 19,659 cm^2, and the pressure was 100 Pa. According to this standard, 10 tests were performed for each type of textile fabric. The thickness of the composites was measured using a similar method.

The areal density or mass per unit area was calculated by dividing the mass of a fabric (or composite) specimen with its area, according to:

$$M = \frac{m}{A} \tag{1}$$

where: M – mass per unit area (g/m^2); A – area of the sample (m^2); m - mass of the sample (g).

As the measurement of the area of a fabric (or auxetic composite) was difficult due to its non-uniform structure, the area was calculated using the digital image correlation (DIC)

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technique combined with the image analysis through ImageJ program. For this purpose, a video of the cut sample along with a ruler placed at the side of the fabric as a reference was captured and then this video was transferred into pictures (frames). The images were next transferred from RGB to binary and finally, the outlines were defined to measure the area. The procedure of the area measurement through DIC technique is illustrated in **Hata! Başvuru kaynağı bulunamadı.**. Fig. 5 (a) shows the real image, Fig. 5 (b) shows the binary image and Fig. 5 (c) represents the outlines of the area to be measured.

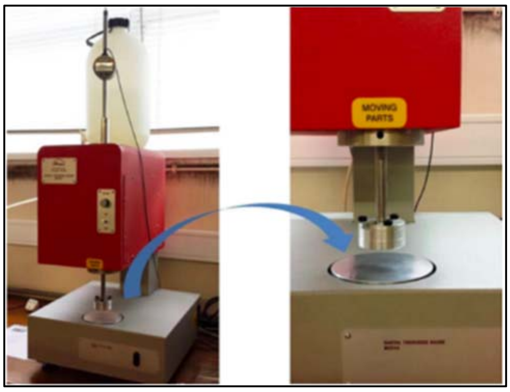
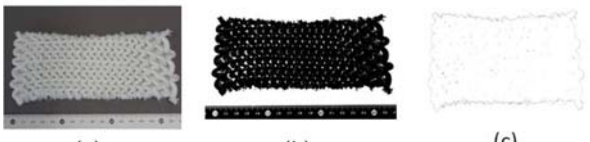


Fig. 4 Measurement of thickness of produced fabrics

To measure Poisson's ratio of the fabrics or composites, longitudinal and transverse strains were measured using DIC method. This measurement setup is shown in Fig. 6. Prior to the measurement, a few white circular points (on black background) were marked on the specimens (Fig. 7). The specimens were fixed vertically to the clamps of a universal testing machine. The displacements of the specimens in both longitudinal and transverse directions were measured using a video camera which performed the recording with 3840x2160 pixels with a frame rate of 24 images/second. The captured video was subsequently processed using MATLAB® software to calculate the strains and Poisson's ratio. Following steps were used by this software to perform this measurement: (1) reading the video, (2) measuring the diameter of the points, (3) analysis of the frames according to the sampling frequency as desired, (4) cleaning the image, (5) identifying nine points based on area, perimeter and eccentricity, (6) calculation of the centroids, areas and perimeters for each point at each frame, (7) measure of the distance between the centroids of the points identified for each frame, and finally, (8) calculate of Poisson's ratio. The image processing steps in MATLAB® are shown in Fig. 8.



(a) (b) (c)

Fig. 5 Different steps to measure the area of a fabric/composite: (a) converting the captured video to an image (b) converting the real image to a binary image and (c) determining the outline of the specimen

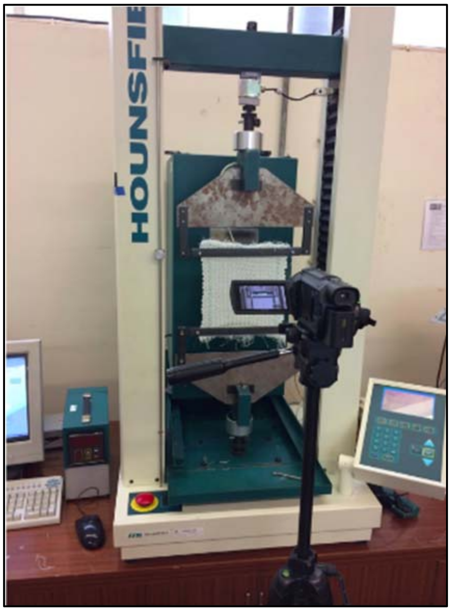


Fig. 6 Setup of testing Poisson's ratio

Fig. 7 Marked points in the fabrics to measure the distance between them

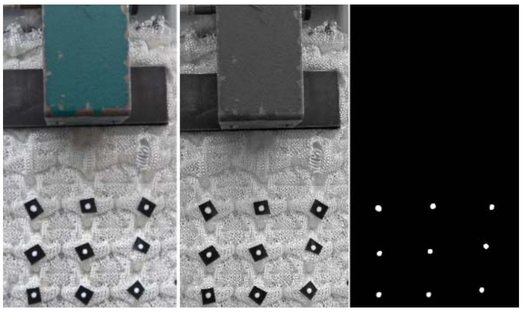


Fig. 8 Image processing steps in MATLAB®

The longitudinal and transverse strains in the samples were calculated using:

$$\varepsilon_x = \frac{x_n - x_0}{x_0} \quad (2)$$

$$\varepsilon_y = \frac{y_n - y_0}{y_0} \quad (3)$$

where: ε_x – Strain in xx direction, ε_y – Strain in yy direction, x_n – Displacement between the points marked at each frame in xx direction, y_n – Displacement between the points marked at each frame in xx direction, x_0 – Displacement between the points marked at the first frame in xx direction, y_0 – Displacement between the points marked at the first frame in yy direction.

III. EXPERIMENTAL RESULTS

A. Physical Properties

The physical properties, namely the thickness and areal density of the plain knit, auxetic fabrics, plain composite as well as auxetic composites are listed in Table IV.

TABLE IV
PHYSICAL PROPERTIES OF PRODUCED FABRICS AND COMPOSITES

Material	Thickness (mm)	Areal density (g/m^2)
Plain Knit Fabric	0.88 (2)*	2.456 (3)
Auxetic Structure 1	7.38 (4)	5.98 (5)
Auxetic Structure 2	9.75 (2)	12.24 (3)
Auxetic Structure 1.1	6.07 (5)	42.63 (5)
Auxetic Structure 1.2	8.35 (3)	64.613 (2)
Auxetic Structure 1.3	7.42 (7)	47.065 (4)
Auxetic Structure 1.4	5.08 (8)	50.840 (8)
Plain Composite	1.57 (12)	4.04 (5)
Auxetic Composite 1	9.70 (9)	9.26 (10)

*the numbers in the brackets are the CV%

It can be noted that the auxetic fabrics had significantly higher thickness as compared to the plain knits produced using the same parameters. This was due to special arrangement of knitted loops according to the re-entrant lozenge design. Among the different auxetic fabrics, the fabrics produced with Kevlar yarns (Auxetic structure 2) showed higher thickness as compared to the fabrics made from polyamide yarns. The auxetic fabrics produced from the polyamide fibres also exhibited difference in the thickness depending on the structural parameters. Similar trend was also observed in case of areal density of the fabrics. The auxetic fabrics had significantly higher areal density as compared to the plain knits and different auxetic fabrics showed considerable difference in the areal density depending on the type of yarns used and the structural or machine parameters. It can also be noted that the auxetic composite possessed significantly higher thickness and areal density as compared to the composites developed using plain knit fabrics.

B. Auxetic Behaviour

The auxetic behaviour of the developed fabric structures is presented in Fig. 9, which shows the change of Poisson's ratio with the longitudinal deformation. It is evident from Fig. 9 that Poisson's ratio of the fabrics was strongly dependant on the longitudinal deformation. In general, the fabrics exhibited higher NPR at lower deformations and as the deformation was increased, the NPR values decreased steadily. The auxetic effect of the developed fabrics resulted from the re-arrangement of the knitted loops under tensile deformation, resulting in opening of the structures and auxetic behaviour. At the higher deformations, the structural re-arrangement became almost complete and as a result, the auxetic behaviour was hardly noticed.

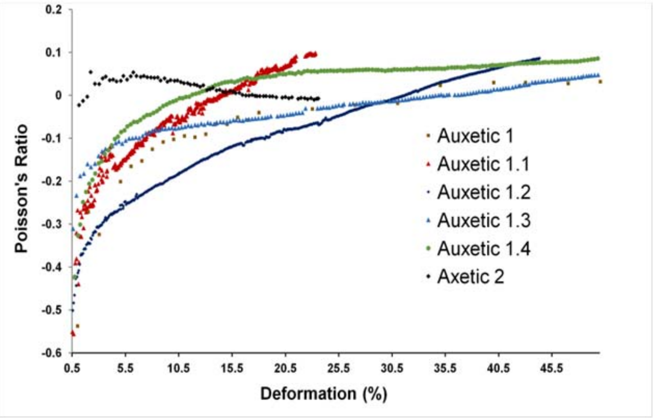


Fig. 9 Variation of Poisson's ratio with the longitudinal deformation of auxetic fabrics

Different fabric structures also showed considerable difference in their auxetic behaviour. The structure 2, i.e. the structure produced from Kevlar fibres, hardly showed any NPR. This was attributed to the fact that the re-organization of the knitted loops and the structural movement were only slightly possible in the Kevlar fibre based fabrics due to the higher rigidity and lower extension of Kevlar fibres.

Among the different auxetic fabrics made from polyamide fibres, significant difference in the auxetic behaviour was observed. Although all of them exhibited NPR values over a wide deformation range, the best auxetic behaviour was observed in case of auxetic structure 1.2, i.e. the structure produced using a loop length of 10 and take down load of 8. The NPR values at ~5% deformation of different auxetic fabrics are listed in Table V.

TABLE V
POISSON'S RATIO OF DEVELOPED AUXETIC FABRICS AT 5% DEFORMATION

Auxetic Structure	NPR at 6% deformation
Auxetic structure 1	-0.17
Auxetic structure 2	+0.05
Auxetic structure 1.1	-0.13
Auxetic structure 1.2	-0.25
Auxetic structure 1.3	-0.10
Auxetic structure 1.4	-0.07

Comparing the auxetic behaviour of auxetic structure 1.1 and 1.2, i.e. the fabrics produced with the same take down load (i.e. 8) but different loop lengths (i.e. 10 and 12), the specimen with lower loop length, i.e. auxetic structure 1.2 showed better auxetic behaviour. The loop length of a knitted fabric decides the tightness or openness of the structure. Knitted fabrics with higher loop lengths possess open fabric structure, which introduces lower tension in the structure and less shrinkage after relaxation [8]. Tighter structures with lower loop lengths, on the other hand, show higher shrinkage after relaxation due to higher internal tension. A knitted structure with more shrinkage at the relaxed state shows more auxetic effect due to more structural changes under deformation [8]. Therefore, the auxetic structure 1.2 probably exhibited superior auxetic behaviour due to its more shrinkage at the relaxed state. Similarly, a comparison of the behaviour of auxetic structure 1, 1.3 and 1.4, i.e. the auxetic fabrics produced using the same loop length but with different take down loads, indicates that the auxetic structure produced with the intermediate take down load (i.e., 8) resulted in the best auxetic behaviour. An increase in the take down load may increase the internal tension and shrinkage in the knitted structure and therefore, can improve the auxetic behaviour [8]. However, at the same time, too high take down load may considerably increase the tightness of the structure and reduce the auxetic effect. Therefore, the intermediate take down load was found to be the optimum for achieving the best auxetic property.

Fig. 10 shows the change of Poisson's ratio with longitudinal deformation of composites developed using auxetic structure 1.2 and the epoxy resin. It can be noticed that the composites exhibited NPR up to 25% longitudinal deformation, after which NPR became positive. The composites developed using the same auxetic fabric but with polyester resin also showed similar auxetic behaviour. However, slightly higher NPR values were obtained with the polyester resins, as listed in Table VI. The polyester matrix was more flexible as compared to the epoxy matrix and this resulted in better structural re-arrangement and movement in case of polyester based composites leading to higher NPR values.

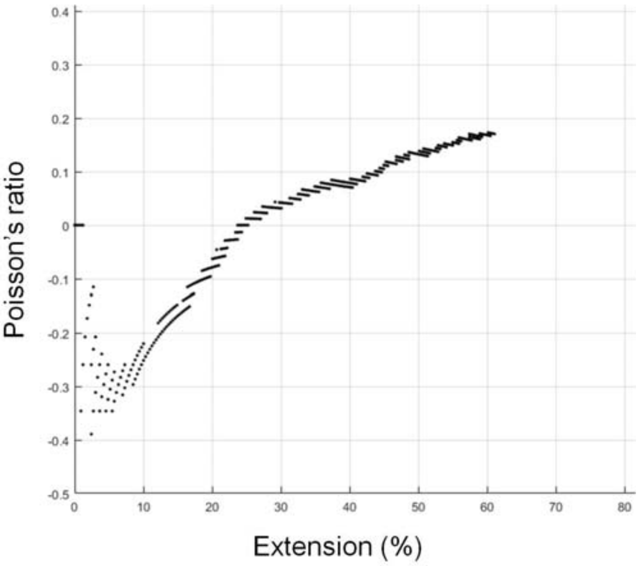


Fig. 10 Variation of Poisson's ratio with the longitudinal deformation of auxetic composites

TABLE VI
POISSON'S RATIO OF DEVELOPED AUXETIC COMPOSITES

Samples	NPR
Auxetic composite 1	-0.35
Auxetic composite 2	-0.5

IV. CONCLUSION

This work reports the first study of developing auxetic knitted fabrics and polymeric composites using re-entrant lozenge design. The auxetic fabrics were produced using the flat bed knitting technology and the influence of the knit loop length and take down load on the auxetic behaviour of the fabrics was thoroughly studied. It was observed that the produced auxetic fabrics possessed higher thickness and areal density as compared to the plain knit fabrics produced using the same parameters. All fabrics produced with the polyamide yarns showed negative values of Poisson's ratio, whereas NPR was hardly noticed for the fabrics produced using para-aramid yarns. An increase in the loop length resulted in the reduction of auxetic behaviour in the polyamide fabrics. Maintaining the same loop length, the best auxetic behaviour was achieved in case of intermediate take down load. The polymeric composites made with the best auxetic fabrics and with two types of polymeric matrices (epoxy and polyester resins) also showed auxetic behaviour. However, the auxetic property was superior in case of less stiff polyester matrix, indicating that the matrix stiffness also had a significant influence on the auxetic effect of the composites. The results of this research demonstrates that the auxetic fabrics and polymeric composites can be developed based on re-entrant lozenge design and their auxetic behaviour can be tailored by adjusting different structural and machine parameters such as type of fibre, loop length, take down load, polymer matrix type and stiffness, etc. In future, mechanical properties of the developed auxetic fabrics and composites such as modulus and strength, energy absorption, impact behaviour, etc. will be studied in detail to investigate the effect of auxetic behaviour on these properties and accordingly, to design materials with suitable characteristics for ballistic applications.

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