Development and Mechanical Characterization of Weave Design Based 2D Woven Auxetic Fabrics for Protective Textiles

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Abstract: Auxetic materials expand in at least one dimension, when stretched longitudinally i.e. they have negative Poisson’s ratio. Development of 2D woven auxetic fabrics (AF) is a new approach to develop mechanically stable auxetic textile structures. However, the mechanical response of such emerging structure is still not studied in detail yet, therefore different mechanical properties of 2D woven AF are compared with conventional non-auxetic fabric (NAF). AF was developed by orienting yarns in auxetic honey-comb (AHC) geometry and auxeticity is induced due to such orientation of yarns. AF was developed using conventional (non-auxetic) materials; cotton yarn and elastane cotton yarn in warp and weft dimension respectively, using air jet loom. Structure and auxeticity of AF were analyzed using a digital microscope and its different mechanical properties (tensile strength, tear strength, bursting strength, cut resistance, and puncture resistance) were studied. AF showed superior mechanical properties with a lower initial modulus, which is beneficial for different protective textiles applications like cut resistance gloves, blast resistant curtains, and puncture tolerant elastomeric composites.

Keywords: Auxetic woven-fabrics, Mechanical properties, Protective textiles

Introduction

Most materials shrink laterally inward, under longitudinal stretch, thus having positive Poisson’s ratio [1]. But according to the theory of classical elasticity, a material can have negative Poisson’s ratio (NPR) as well. NPR (Auxetic) materials show an increase in at least one lateral dimension when stretched longitudinally [2]. Auxeticity is structure or geometry dependent phenomena. Rotating units, chiral anti-chiral, re-entrant etc are different classes of auxetic geometries which are visualized in materials from micro to macro-level, to impart auxeticity [3]. Special deformation behavior of such geometries induces auxetic nature in the materials.

Auxetic textiles have attracted great attention in the recent era. Researchers have tried to induce the auxetic behavior from fiber to fabric level, by visualizing auxetic geometries in the textile structures. Auxetic fibers were developed through the modification of conventional melt spinning route. Auxeticity is imparted in nylon, polypropylene, polyester etc. at fiber spinning level [4-7]. Auxetic fibers based composites showed superior mechanical properties because NPR induces self-clinging effect and higher pull-out resistance in auxetic fibers [4]. But, the high cost of auxetic fibers is a major limitation in their commercialization. Auxeticity was therefore introduced at yarn level by simple wrap spinning technique. Fine high modulus yarn was wrapped over coarser low modulus yarn, to make helical auxetic yarns. Woven fabric and corresponding auxetic composites of auxetic yarns also showed NPR and superior mechanical properties [8-11]. But, low modulus of helical auxetic yarns limits their high-speed processing on conventional weaving machines.

Inducing auxeticity at fabric level is therefore of interest, as it has continuous manufacturing, low cost, and no material limitation. Knitted structures are mostly focused on the development of auxetic structures, for their flexibility and versatility in design manufacturing. Weft knitted [12,13] and warp knitted [14-16] AFs are developed using non-auxetic materials. But due to the lower structural stability of knitted structures, weaving technology is combined with knitted structures to make the stable co-weave knit auxetic structures. Numerical and mathematical modeling of different parameters of geometry and its composites were developed and tested for energy absorption and impact applications [17-21]. Composites made by associated co-weave-knit structures also showed auxeticity. A special machine was designed for the development of such structures but using conventional machines such structures cannot be developed. In our previous work, 3D woven auxetic structures were developed, using conventional weaving machine. 3D woven auxetic fabrics were manufactured using a combination of different modulus natural fibers yarns. 3D woven auxetic structure based composites showed higher impact resistance than the conventional 3D woven composites [22].

Recently, a great focus has been given to the development of 2D woven AFs, because by such structures, superior mechanical properties of AFs can be utilized for the wearable protective devices. By utilizing differential shrinking property of different weaves, auxetic geometries are visualized in woven fabrics. By this method, high strength
auxetic materials with continuous production could be developed, just by weave design variation [23]. Amongst all auxetic geometries, AHC geometry showed best auxetic nature [23,24], therefore AHC is focused here. In our previous work, comfort properties of 2D woven AF and non-auxetic fabric (NAF) were compared (Ali et al., in press), where AHC geometry based AF showed superior comfort properties, and AFs were also tested for different medical and wearable applications.

Woven AFs are claimed to have high stability and strength, but their mechanical response is not studied in detail yet. It is important to know that, how 2D woven AFs deform under different kinds of mechanical loads, to use them for different technical devices. But up to best of our knowledge, mechanical behavior of 2D woven AFs focusing protective textiles is not studied in detail yet. Therefore, 2D woven AF is developed and its auxetic and mechanical properties are compared with conventional NAF, to check its potential in different protective textile applications. Using the same principle as reported by others [23,25] here auxetic geometry is visualized in a single layer fabric (instead of double layer fabric) so that irregular surface texture can be avoided. NAF has straight yarns, due to which it shows a lower elongation at break with relatively high initial modulus. Due to such nature, NAF has a lower tolerance to tear, cut, and burst, thus leading to lower protection levels. By auxetic orientation of yarns, higher elongation at break and synclastic curvature adoption can be induced, thus leading to the superior protective nature of woven fabrics.

**Experimental**

**Basic Weaves and Auxetic Fabric Design**

Interlacing pattern of warp and weft is defined by the weave design; which is explained by interlacements (warp above weft or weft above warp) between two groups of yarns. Three basic weave designs are commonly used, i.e. plain, twill, and satin (Figure 1(a)), whereas, other designs are modifications or derivatives of these three designs. Amongst all weaves, plain weave has highest possible interlacements, where all yarns are interlaced consecutively. Whereas, in twill weave and satin weave, yarns are interlaced in a diagonal fashion and a random fashion respectively. Most importantly, in twill and satin weave, yarns are passing straight in between two consecutive interlacements. This gap in between two consecutive interlacements is called float length, as highlighted with double head arrows in Figure 1(a).

Shrinkage behavior of fabric on relaxation (after getting off-loom) is strongly dependent on the float length and density of interlacements. Highly interlaced structure and non-interlaced structure adopt the shape as explained in Figure 1(b). Highly interlaced structure (low float length) limits the high shrinkage because the interlacing weft keeps the warp yarns at a higher spacing from each other. This spacing not only keeps the yarns expanded but it also makes the fabric structure to be stiff/packed/tight in the respective position. On the other hand, exactly opposite behavior is observed in a non-interlaced structure (high float length), in which the warp yarns tend to bundle up as shown in Figure 1(b). This bundling up of warp is rendered because of the lateral stretch applied by the weft yarn, due to its shrinkage on relaxation. Conclusively, depending on variation in float length, the packing or shrinkage of yarns can be controlled. A structure having average float length of highly interlaced and non-interlaced structure will be having an average shrinkage as well. Arranging highly interlaced and high float length structure consecutively, the warp yarns can be oriented at different angles as per requirement as shown in Figure 1(b).

Based on the differential shrinkage in the differential float length structures (as explained in above section), the AHC geometry is visualized in the fabric structure. The arrangement of highly interlaced, medium interlaced and high float structure is shown schematically in Figure 2(a). Where it can be observed that there are continuous vertical ribs (along warp), made of the highly interlaced structure. These ribs keep each auxetic cell unit separate and also provides the integrity to the fabric structure [23]. While the horizontal ribs have highly interlaced and non-interlaced structure alternatingly. Also, this pattern is reversed in every next horizontal rib, in such a way that the warp yarns change...
Mechanical Characterization of 2D Woven Auxetic Fabrics

from the highly interlaced to high float structure in an exactly same manner as it is in AHC geometry. In between two horizontal ribs, the satin weave is used that has medium or average interlacements, lesser interlacements can assist the reorientation of yarns in consecutive reorientations.

Yarns are straight during weaving (Figure 2(a) left) but after de-sizing and relaxation, the yarns orient themselves in AHC geometry. The auxetic orientation of yarns and the relaxation behavior or highly interlaced structure and non-interlaced structure is highlighted in red color in Figure 2(a; right). Similar geometry can also be observed in microscopic view of AF; made by utilizing the differential shrinking of just three yarns. By visualizing the geometry on three yarns, the orientation angle of warp yarns is 159.5°, instead of 180°; as it is in conventional NAFs. By increasing the number of yarns participating in the differential shrinking the orientation angle and the corresponding auxeticity can be varied [23]. The same effect can be observed by comparing Figure 2 and Figure 3(d), where the yarns are oriented at angle of 159° and 145°, respectively. Here, the size of the auxetic unit is visualized by using differential shrinking of fifteen yarns, while four plain woven yarns were used for making vertical ribs. This geometry was optimized after testing the different variations in size of AHC cell, including the number of threads participating in AHC unit, different auxetic geometries, the elastane percent of the weft, fabric density etc.

Materials and Experimental Method

AF and NAF (3/1 twill weave) both were made with same specifications and materials, just based on the difference in weave design, the auxeticity was induced and corresponding change in mechanical properties is studied. 3/1 twill woven fabric was selected for comparison with the AF because crimp percent and an average float length of this structure are equal to AF. Hence, float length dependent variation in the mechanical properties of fabrics can be omitted. Cotton yarn of 29.5/1 Tex and Elastane-cotton core spun yarn of 29.5/1 Tex (with 1.2 Tex lycra yarn) were used in warp and weft respectively. Before weaving, warp yarns were sized (5 %) with starch and PVA mixture to assure high-speed weaving. Samples with 44 ends per cm and 20 picks per cm were weaved on Picanole Omni-Plus-X air-jet loom, equipped with electronic dobby shedding system. Same machine settings and fabric specifications were maintained during the weaving of both samples. Samples developed were de-sized using enzymatic (Bactasole) treatment at 80°C for 40 minutes and after complete drying, samples were subjected to further characterization.

Testing Methods

Fabric structure was analyzed optically at different stages of development using 1000× digital microscope (equipped with Scoope image plus software). Auxeticity of AF was characterized by measuring lateral and longitudinal strain in points marked on the fabric strip under constant strain. The controlled strain was applied by Universal Testing Machine (LLOYD LRX Plus Ametek, USA), while the sample dimensions were kept 100 mm×50 mm. The same microscope was also used for measurement of displacement between the points with high accuracy.

The tensile strength of fabric was tested on the same universal testing machine, following ISO-13934-1 standard test method. The sample size was reduced to 100 mm×50 mm, due to high elongation in weft and speed during the test was 100 mm/minute. Tear strength test was carried out to know cut propagation behavior in both fabric structures by following ISO 13937-1 standard testing method. Standard method EN-388 was followed for the samples testing, in which fabric sample was clamped in jaws, with exposed 20 mm diameter circle. Standard testing method D3786 was followed to analyze bursting strength of fabrics, on bursting strength tester (SDL ATLAS, USA; P1000-M2298). During testing, sample was clamped in circular jaws with a rubber diaphragm of 300 mm diameter, at center. Cut resistance level was measured by vertical blade cutting method following BS EN 388: 2016 & 6.2 standard testing method, and an average of four values was considered as a final cut
resistance value.

**Results and Discussion**

**Fabric Structure Analysis**

AF structure was analyzed at different stages of processing and changes in geometry were analyzed. The dimensions of highly interlaced and high float structure just after getting off loom were 70.5 mm and 64.7 mm respectively. The orientation of angle of warp yarns due to this difference was 172.7° degrees, as shown in Figure 3(a), while dimensions of highly interlaced and high float structure before de-sizing are shown in Figure 3(b, c). The change in orientation angle and differential shrinking become more prominent after de-sizing and final relaxation. Before de-sizing, highly shrinking structure was tested to be 64.7 mm (Figure 3(c)), however after de-sizing the structure is shrunk to 28 mm (Figure 3(e)). As the difference of shrinkage between high shrinking and low shrinking structure is very high i.e. their final dimensions are 28 mm (Figure 3(e)) and 64 mm (Figure 3(f)), thus AHC geometry can be clearly visualized in fabric structure. The orientation angle of yarns in final AHC geometry is 145° (Figure 3(d)), unlike conventional fabric having straight yarns having an angle of 180°/0°. Microscopic images highlighting the dimensions of highly interlaced and high float structure are shown in Figure 3(a-c).

![Figure 3](image)

*Figure 3.* Auxetic honeycomb structure in auxetic fabric (a) orientation angle of yarns before de-sizing, (b, c) dimensions of highly interlaced and high float structure before de-sizing (d) orientation angle of yarns after de-sizing, and (e, f) dimensions of highly interlaced and high float structure after de-sizing.

![Figure 4](image)

*Figure 4.* NPR characterization of AF (a, b) warp-wise NPR, whereas warp yarn are horizontal, (c, d) weft-wise NPR, whereas warp yarns are vertical.
Negative Poisson’s Ratio Characterization

**Warp Wise NPR Characterization**

Every high float structure is supported by the highly interlaced structure, in warp dimension. So, as the longitudinal load is applied, the highly interlaced structure creates laterally outward push on the high float structure. This outward expansion causes an increase in dimensions of high float structure, thereby causing an outward expansion in whole fabric structure. This effect is further clearly demonstrated in small auxetic cell structure (Figure 2(b)). Whereas similar effect can also be observed in Figure 4(a,b), in which the high float structure is 24 mm in a relaxed state, whereas in stretched condition it is increased to 43.5 mm. Length of high float yarn was 24 mm (on fabric back) before stretch, but after warp-wise strain, it was increased to 43 mm in lateral dimension (Figure 4(a,b)). 10 mm strain in longitudinal dimension produced 12 mm lateral strain, as clearly shown in Figure 4(a,b). The initial distance between points and warp-wise auxeticity in the fabric is given in Table 1. The NPR in warp direction is relatively high, but the strain is much lower, as compared to the weft direction.

**Weft Wise NPR Characterization**

Under normal conditions, warp yarns are oriented in zigzag pattern due to differential shrinking. When AF is stretched along weft, warp yarns get straight, as the bending of warp yarns is because of weft shrinkage. This warp straightening causes an increase in fabric dimensions along warp, thus giving rise to weft-wise NPR. As it can be seen in Figure 4(c, d), where the distance in between two rows is 72.7 mm under the slightly stretched condition and it is increased to 75.8 mm under higher stretched condition. Weft wise NPR characterization values are given in Table 1. Similar mechanism can also be observed more clearly in small-sized auxetic cell added in Figure S2(b). Auxetic structure in fabric can be observed before and after de-sizing in Figure S3.

**Tensile Strength**

Tensile strength curves of both samples, for warp and weft direction, are shown in Figure 5. Breaking load along warp of AF and NAF was 911 N and 608 N respectively, i.e. AF has 50 % higher tensile strength. Elongation at break along warp of AF was also 6 % higher than NAF. Weft wise elongation at break for AF and NAF was 230.4 mm and 187 mm, i.e. AF has 22.7 % higher elongation at break. Similar trend was observed while testing tensile strength along weft, i.e. breaking load was observed 193.9 N and 170.1 N for AF and NAF respectively, i.e. AF has 14 % higher (weft-wise) strength than NAF.

It is clear from the Figure 5 that AF has lower modulus initially, but after a certain limit, there is a fast increase in modulus. In AF, yarns are in zig-zag orientation to make AHC pattern, and even by small stress, this angled orientation of yarns tend to get straighter; thereby rendering higher

| Table 1. Poisson’s ratio and displacement in points marked for NPR characterization |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Longitudinal ∆L (mm)            | Lateral ∆L (mm)                | Longitudinal ∆L/∆L = $\epsilon_{long}$ | Lateral ∆L/∆L = $\epsilon_{lat}$ | Poisson's ratio $\frac{\epsilon_{lat}}{\epsilon_{long}}$ |
| Warp                            | 10                              | 12                              | 0.140                           | 0.18                            | -0.77                           |
| Weft                            | 15.7                            | 4.1                             | 0.328                           | 0.056                           | -0.17                           |
initial elongation. Higher initial elongation renders lower initial modulus, but after when the yarns are straight, there is a faster increase in modulus. Also, due to angular (zig-zag) orientation of yarns, AF has a higher elongation at break. Contrary, NAF has a relatively uniform modulus, because crimps open uniformly under the stress. In AF, there is outward lateral pull on the weft, when the sample is stretched longitudinally and vice versa. Stress is applied on the warp, but some of its energy is also absorbed in weft stretching, hence weft also contributes in warp strength/energy absorption and vice versa. For the reason, the auxetic structure has higher strength. On the other hand, there is inward lateral shrinkage in NAF, so weft or warp yarns are participating in energy absorption individually, hence absorbing lower energies under tensile stress.

**Puncture Resistance Test**

Puncture strength of AF and NAF was tested to be 244.38 N and 269.5 N respectively, as shown in Figure 6. AF showed 9.3 % lower puncture strength, but an extension to puncture for AF and NAF was 10.835 mm and 9.93 mm respectively, thus AF has 9 % higher extension. There is much difference in ultimate puncture force, but energy absorption of both samples was approximately same under puncture test. Energy absorption of AF and NAF was 779 and 774 joules i.e. no significant difference in energy to puncture was observed.

Initially, when the stylus is not in touch with fabric, puncture strength curve is zero for both samples. But, when the stylus touches the fabric, the curves start rising. Higher puncture tolerance of NAF can be attributed to its uniformly jammed structure. But in AF, it is easy to pass through lesser jammed/high float portion. Inter-fiber friction is less due to lesser interlacements in medium interlaced and high float portions; therefore stylus can push the yarns aside easily, thus making it possible to puncture at lower stress. Puncture tolerance of AF up to higher strain can be attributed to its higher extension and adoption of the shape of the stylus (tip) during extension. Bi-extensibility of AF, induced by NPR, enables AF to accommodate higher bi-dimensional deformation. Moreover, during extension of warp, weft yarns are also contributing to energy absorption as explained in the tensile test section, thus contributing to puncture energy absorption. Bi-dimensional expansion is not possible in NAF, so lower extension and equal energy absorption were observed. A major reason for lower strain tolerance in NAF is the lower extension in straight warp yarns, which cannot reorient themselves along with puncturing body. Based on this test, AF is not suitable for applications like ballistics, where higher elongation cannot be tolerated. But it is quite suitable for elastomeric composites-based applications like tires; where tolerance to a higher extension before puncture is of critical importance.

**Tear and Bursting Strength**

The initiated cut was only propagated 2 mm in AF when subjected to tearing test. Tear tolerance of AF can be due to a high extension in AF, where tearing hammer touched the extreme limit of extension before tearing full sample. On the other hand, NAF sample was completely torn apart into two pieces, as shown in Figure 7(a). According to the testing procedure, the hammer size is increased, when the sample is not torn apart, but the hammer is bounced back in that case. Whereas, during testing of AF, the hammer touched its extreme position, but tear cut propagated only 2 mm. Although the hammer size was increased, the sample was not torn. This non-tearing behavior can be attributed to high initial elongation and tear impact absorption of the auxetic structure. High initial elongation makes the sample to remain untorn even at maximum elongation of tearing test. Microscopic analysis of tear cut stopping point shows that cut stops at high float structure, as shown in Figure 7(a). As all yarns in S2 are resisting simultaneously against the cut (because bundled together), so their resistance is higher. In the relatively jammed structure of NAF, yarns are torn easily, as yarns are not resisting simultaneously.

Bursting strength test was carried out to compare the response of material under bi-dimensionally expanding force. Instead of bursting, AF completely adopted the shape of the inner groove, formed for bursting strength test. The force required to adopt the shape of bursting semi-sphere is much less than the bursting strength of NAF i.e. 44 N, whereas NAF strength is 611 N, as shown in Figure 7(b). This test clearly shows that the AF has better tendency to get shaped under bi-dimensional stress applied. The total force (at maximum extension) was higher for shaping the AF, but the major portion of that force is contributed by the

![Figure 6. Comparative analysis puncture resistance of fabric structures.](Image)
correction factor (force applied on the extension of rubber). Due to a higher extension in AF, its correction factor is also higher, but there is no energy consumed in breaking of yarns, therefore the ultimate strength of the AF is lower. Bursting force consumed in AF testing is just because of extension and reorientation of auxetic geometry.

**Cut Resistance Test**

Cut resistance of the fabric is important in applications like cut resistant gloves, used in the handling of sharp objects. AF showed cutting index of 1.8 and 2 in weft and warp dimensions respectively. On the other hand, NAF showed cutting index of 1.23 and 1.28 in weft and warp direction respectively, as shown in Figure 8. AF showed 56.2 % and 46.3 % higher resistance to cutting than NAF, in both directions. It is also worth noting that warp cut resistance value of both (AF and NAF) samples is higher than weft cut resistance.

The higher cut resistance of AF can be attributed to synclastic curvature adoption, thus rendering higher surface area in contact with the blade. When same force is distributed over a larger area, its pressure/cutting effect is considerably reduced. Reorientation-ability of AHC structure is also playing a major role in higher cut resistance of AF. Because

![Figure 7](image)

**Figure 7.** (a) Torn non-auxetic woven fabric (left), incomplete tearing of auxetic fabric (right) and (b) bursting strength of auxetic and non-auxetic fabric.

![Figure 8](image)

**Figure 8.** Comparison of cut resistance of auxetic and non-auxetic fabric.
of AHC pattern, yarns try to elongate and reorient, before cutting. Whereas, yarns in NAF have jammed structure and no reorientation-ability, hence straight yarns are cut directly (easily), thus showing lower cut resistance. Both samples showed higher resistance in the warp direction because thread density is high in warp dimension. As higher auxeticity showed higher resistance in the warp direction because (easily), thus showing lower cut resistance. Both samples no reorientation-ability, hence straight yarns are cut directly cutting. Whereas, yarns in NAF have jammed structure and of AHC pattern, yarns try to elongate and reorient, before passing through. Conclusively, AFs can outperform against the mechanical loads where elongation and reorientation-ability are of primary importance like in cut resistant, bursting resistant, and energy absorbing articles (seat belts) etc., especially in applications like cut resistant gloves, blast resistant curtains etc.

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Conclusion

Auxeticity was successfully induced in (single layer/2D) woven fabric structure by visualizing AHC geometry in fabric structure. The shrinkage difference induced by different weaves were strong enough that AHC structure can be clearly visualized. AF showed NPR of -0.77 and -0.17 along the warp and weft direction, respectively. Mechanical properties of AF fabric were compared with conventional NAF, both made with same specifications and loom settings. AF showed 50 % and 14 % higher tensile strength than NAF in warp and weft direction respectively. Higher elongation at break and higher energy absorption was also observed in AF, under tensile loading. Under tearing test, NAF was torn completely but AF absorbed tearing impact, with negligible cut propagation. Similarly, AF adopted the bursting tester hemisphere groove without bursting, whereas NAF was burst completely. Cut resistance of AF was also 56 % (warp) and 46 % (weft) higher than NAF, because of high strength and the high contact area between blade and fabric. On contrary to it, puncture resistance for NAF was higher, due to high packing. The puncturing body can push the yarns of loosely interlaced portion aside thereby making its way to pass through. Conclusively, AFs can outperform against the mechanical loads where elongation and reorientation-ability are of primary importance like in cut resistant, bursting resistant, and energy absorbing articles (seat belts) etc., especially in applications like cut resistant gloves, blast resistant curtains etc.

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