DOI: / ((201900156))
Article type: Full Paper

Single and double layered bi-stretch auxetic woven fabrics made of non-auxetic yarns based on foldable geometries

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Abstract: Auxetic fabrics made of non-auxetic yarns have gained increasing interest of textile scientists. Most recently, single layered bi-stretch auxetic woven fabrics made of non-auxetic yarns based on parallel in-phase zig-zag foldable geometry have been reported to have auxetic behavior when stretched along both principal directions. It has also been reported that this geometry could possibly be realized into double layered woven fabrics. Additionally, it has been suggested that the phenomenon of differential shrinkage could be exploited to realize another variation of foldable geometry such as out of phase zig-zag foldable structure into woven fabrics. Therefore, this study aimed to explore these two possibilities. Both double layered auxetic woven fabric based on parallel in-phase zig-zag foldable geometry and single layered fabrics based on out of phase zig-zag foldable geometry were developed by using the phenomenon of differential shrinkage to realize these geometries into the woven fabric structures. Five different auxetic woven fabric samples were fabricated using elastic and non-elastic yarns on a conventional weaving machine and tested along two principal directions. The testing results showed that all the developed fabrics have auxetic behavior in both principal directions and the placement of weaves and weft yarn arrangements have an obvious effect.

Keywords: auxetic; bi-stretch; lateral contraction; out of phase zig-zag geometry; negative Poisson's ratio

1. Introduction

Auxetics materials have a negative Poisson's ratio. In contrast to most conventional materials, auxetic materials possess the property that become fatter when stretched and narrower when compressed [1-3]. The term auxetic means "that which tends to increase". It was first derived from the Greek word (auxetikos) by Evans K [4]. It is reported that the auxetic behaviour is responsible for improvement of several intriguing properties. These properties include shear modulus, energy absorbance, vibration damping [5-9], sound absorption [10], indentation resistance [11-13] and synclastic behavior for better formability [14]. The known naturally and manmade auxetic materials include metals [15], laminates [16], gels [17], crystalline structures [18-20], polymers [21, 22], composites [6, 8, 23], foams [1, 24] and textile materials including fibers [22, 25], yarns [26-30] and fabrics including woven fabrics [26, 27, 31-37], weft knitted fabrics [38-43], warp knitted fabrics [44-47], 3D textile structure [48, 49], and non-woven fabrics [50].

Auxetic woven fabrics made of non-auxetic yarns [31-35] have gained extra ordinary interest of researchers in modern times. The conventional woven fabrics have positive Poisson's ratio which means that they undergo contraction in transverse direction upon stretch in longitude direction [51, 52]. In certain clothing applications such as clothing for maternity, under garments, shape wear, leggings and sportswear, the behavior of fabric in lateral direction is significantly important. In case of a garment made of conventional fabrics, the lateral contraction results in discomfort and poor shape fitting especially at joint parts [34, 53]. Conversely, the auxetic woven fabrics possess negative Poisson's ratio (NPR) and they become wider in lateral direction as well when stretched in longitude direction [31-35]. Therefore, in case of a garment made of auxetic woven fabric, the deformation of the fabric is consistent with body movements, resulting in improved comfort and shape fitting [14, 34, 54].

Most commonly, two techniques have been adopted to produce auxetic woven fabrics. The first is to fabricate auxetic fabrics by using helix auxetic yarns and weaving technology. This method is adopted to produce auxetic woven fabrics with helical auxetic yarns in warp [26] or weft [27, 36]. It is reported that the developed fabrics may have certain limitations like low auxetic behavior and difficult in manufacturing. In addition, the true auxetic behavior of the auxetic yarns cannot be fully transferred to the fabric structure because of woven fabric structural limitations. The second technique is to fabricate auxetic fabrics from non-auxetic yarns (yarns having positive Poisson's ratio) by realizing an auxetic geometry capable of inducing auxetic behavior into the fabric structure [51]. Previously, this technique was used to produce auxetic knitted fabrics and recently is employed to the development of single layered and double layered uni-stretch and bi-stretch auxetic woven fabrics [31-35]. The developed auxetic knitted fabrics based on this technique are mostly produced on laboratory scale because of complicated geometrical structures. In addition, the limitations like low structural stability, low elastic recovery and higher thickness restricted their use in many applications.

On the other hand, the reported uni-stretch auxetic woven fabrics based on foldable geometries and double layered auxetic woven fabrics based on re-entrant hexagonal geometry have extensibility and low auxetic behavior only in one direction. The double layered uni-stretch auxetic woven fabrics are based on foldable convexities running along warp direction, they also have extensibility only in one direction and produced zero Poisson's ratio when stretched along weft direction [34]. Most recently, the development of single layered bi-stretch auxetic woven fabrics based on foldable geometry and re-entrant hexagonal geometry by using this technique has also been reported [31-33, 35]. These fabrics which have extensibility and auxetic behaviour in both principal directions are named as bi-stretch auxetic woven fabrics. These fabrics showed a larger auxetic behavior when stretched along both warp and weft directions. Moreover, it is reported that the weft yarn arrangement and float length of loose weave have a significant effect on the auxetic behavior of auxetic woven fabrics. In case of weft yarn arrangements, the fabrics with all elastic yarns in weft produce higher auxetic behaviour as compared to that produced by the fabrics with alternate elastic and rigid yarns. In case of float length of loose weave, it is found that the largest float length of loose weave could not produce higher auxetic effect. It is also suggested that using the same technique and weft yarn arrangements other auxetic geometries should also be investigated [31, 33].

Zulifqar et al. [34] suggested that the parallel in-phase zig-zag foldable geometry can possibly be realized into double layer fabric. Correspondingly, Cao et al. [33] proposed that by exploiting the phenomenon of non-uniform contraction profile within the unit cell of fabric structure, another variation of foldable geometry like out of phase zig-zag foldable geometry can be realized in to a woven fabric structure. Therefore, in this study, the developments of double layered auxetic woven fabrics based on parallel in-phase zig-zag foldable geometry and single layered auxetic woven fabrics based on out of phase zig-zag foldable geometry are reported. The phenomenon of differential shrinkage or non-uniform contraction profile is exploited to realize these geometries into the woven fabric structure. The auxetic nature of the fabrics were tested when stretched along two principal directions. The developed fabrics showed the NPR effect in both stretch directions which is found to be influenced by the weft yarn arrangements and by the placement of loose weave within the unit cell of interlacement pattern.

2. Experimental

2.1. Design concept and auxetic geometrical structures used

Because the Poisson's ratio is an elastic constant and is independent of the material scale, auxetic materials can be single molecules or a structure of macroscopic to micro level [1]. Auxetic materials can be made based on two different approaches: the top-down approach which involves the manipulation of everyday polymers to give the desired structure and properties, and the bottom-up approach in which the material is built by molecules. In both techniques, the main objective is to create a repeating pattern of unit cells which possess the hinge-like features [1, 3]. Structural modification is one of the various mechanisms leading to auxetic effect [18, 19, 31, 33, 42]. Therefore, a simple molecular design approach is based on producing the auxetic materials by modifying the macrostructure of the material [4, 22]. One such example is materials which possess hinge-like features and they can extend in longitudinal as well as in transverse direction when a tensile force is applied [31, 33, 42]. This approach is adopted in this study and through structural modification of fabric structural unit cell, a repeating pattern of foldable unit cell capable of exhibiting auxetic behavior is realized into woven fabric structure.

It is reported that the foldable structures can be unfolded when stretched in one direction, increasing the dimensions in the lateral direction, thus enabling auxetic behavior to be achieved [33, 34, 40, 42]. Such foldable structures have already been realized in uni-stretch and bi-stretch auxetic woven fabrics by creating the phenomenon of differential shrinkage in the woven fabric structure. This phenomenon can be created using a combination of weaves with different contraction/shrinkage properties and using elastic and non-elastic yarns. When such a fabric is relaxed, the differential shrinkage phenomenon enables the unit cell of the fabric structure to occupy a non-uniform contraction profile, and the sections of fabric with the different tightness of weave undergo different levels of shrinkage and the folds are created. Upon stretching, the unfolding originates with a spread of folded area not only in the stretch direction but also in the transverse direction, giving rise to the NPR effect. Therefore, the NPR effect results from the interplay between the interlacement pattern of warp and weft, different stretch properties of the elastic and non-elastic yarns, and the mechanism of deformation of the fabric [33, 34]. This method is adopted to produce the double layered and single layered fabrics in this study. To achieve the NPR effect in both directions, double-directional folds are created with the ability to spread in two directions upon stretching by creating the phenomenon of non-uniform contraction profile in both warp and weft directions.

In this study, the double layered fabric is produced based on the geometry as shown in Figure 1(a). The architecture of this foldable geometry consists of alternate double-directional unstitched (where the two layers are detached) folded stripes and self-stitched (where the two layers are attached together) flat strips placed in a parallel in-phase zig-zag fashion running along the weft direction with a connecting angle of 45°, which allows the design of a symmetric interlacement pattern. The minimal repeating unit or unit cell of geometry is highlighted by red color box as shown in Figure 1(a). When this double-directional folded structure is subjected to an extension in warp or weft direction, the structure also expands in the lateral direction due to the opening of double-directional unstitched folded sections in two directions, resulting in an NPR effect as shown in Figure 1(b-c).

Figure 2 and 3 show the geometries used to produce two single layered fabrics. In the geometrical structure as shown in Figure 2, the double directional folded stripes are created in parallel out of phase zig-zag fashion runing along weft direction. The spaces formed between these stripes are created as flat section and may form a parallelogram shape. However, in the geometrical structure as shown in Figure 3, the double directional folds are created at the central parallelogram sections while the parallel out of phase zig-zag strips runing along weft direction are created as flat. The minimal unit cells are highlighted by dashed lined box as shown in Figure 2-3(a). When these structures are subjected to an extension in either warp or weft direction, the structures also expand in the lateral direction due to the flattening of the folded out of phase zig-zag stripes in case of geometrical structure shown in Figure 3 or the folded central parallelogram sections in case of geometrical structure as shown in Figure 4. Therefore, the transverse dimensions of the structure increases resulting in NPR effect as shown in Figure 2(b)-3(b) and 2(c)-3(c). Thus, it can be established that in case of auxetic geometries as shown in Figures1-3, the mechanism of achieving auxetic effect is based on a configuration of the geometrical unit cell such that upon extension the unit cell expands not only in longitude direction but also in transverse direction.

2.2. Design of interlacement pattern, fabrication and testing of NPR

The structural unit of a woven fabric is termed as the weave of the fabric and it is the interlacement of warp and weft yarns in a predefined configuration. It is presented by a square grid in which horizontal and vertical lines depict the weft and warp yarns respectively. Each square shows the interlacement point of warp and weft yarns. The filled square means that the warp yarn is over the weft yarn while the blank means that weft yarn is over the warp yarn at the corresponding place in the fabric. Numerically, the weave can be written as $\frac{A}{B}$, where A represents the number of warp yarn over weft yarn and B represents the number of weft yarn over warp yarn. A is also known as float length of the weave. The repeat R is the sum of two numbers $A + B = R$ which states that after every R warp yarns or weft yarns the interlacement pattern is repeated. The most rigid and tight weave is plain weave. It has the maximum number of possible interlacements of warp and weft yarns and written as 1/1 which means that the warp yarn runs over and under the weft yarn in an alternate fashion as shown in Figure 5(a-b). On the other hand, 4/1 weave is less tight than plain weave because it has a smaller number of interlacements per repeating unit. In this weave each warp yarn runs over 4 weft yarns and under 1 weft yarn as shown in Figure 5(a-b) [52]. In this study plain 1/1 weave and 4/1 weave are used to design the interlacement patterns.

The double layered fabric named as IZZF-2 is designed and fabricated based on parallel in-phase zig-zag geometry. The unit cell of the interlacement pattern for this fabric is shown in Figure 4. In this fabric, alternate elastic and non-elastic yarns are used in both warp and weft direction. In Figure 4, letters “F and B” represent yarns of face and back layers respectively, and letters “R and L” represents non-elastic and elastic yarns respectively. The two sets of warp yarns are interlaced with two sets of weft yarns, where the elastic weft yarn is interlaced with non-elastic warp yarn employing plain weave in the face layer and elastic warp yarn is interlaced with non-elastic weft yarn employing plain weave in the back layer, as shown in the Figure 4. The two fabric layers are self-stitched and kept unstitched in alternate parallel in-phase zig-zag stripes manner running along weft direction. The shaded cells in parallel in-phase zig-zag manner represent the un-stitched section of the fabric, whereas shaded cells with mark "X" and "0" at the self-stitched section represent the stitching points of two layers. Additionally, the shaded cells with mark "X" represent positions where the warp yarns are raised over the weft yarn and cells with mark "0" represent positions where warp yarns are lowered under weft yarns. Previously, this method has already been reported to produce uni-stretch auxetic woven fabrics based on foldable convexities [34]. However, in this study, the same method is applied to produce bi-stretch double layered fabrics based on zig-zag foldable geometry. It is assumed that upon relaxation at unstitched section of the fabric, because of shrinkage of elastic weft yarn in the face layer and elastic warp yarns in the back layer, the folded strips can be formed on the face of the fabric in parallel in-phase zig-zag manner.

It is also reported that to create non-uniform contraction profile within the unit cell of a single layered fabric structure, the combinations of loose weave and tight weave along with elastic and non-elastic yarns must be used [34]. This method has been adopted to fabricate uni-stretch and bi-stretch auxetic woven fabrics based on foldable geometries. In the design of interlacement pattern for those fabrics, the loose weave and tight weave strips are arranged alternately in parallel in-phase zig-zag fashion running along weft direction s [33, 34]. In this study, the same approach is adopted to produce four single layered bi-stretch auxetic woven fabrics, including OZZF-A1, OZZF-A2, OZZF-B1 and OZZF-B2. The unit cells of interlacement patterns for these fabrics are shown in Figure 5(a-b). 1/1 Plain weave is used as tight weave while 4/1 weave is used as loose weave. In addition, the cells with mark of "0" represent positions where warp yarns are lowered just to break the too long float which is formed because of the long floats of adjacent yarns. In fabrics OZZF-A1 and OZZF-A2, the 4/1 weave was placed at the central parallelogram shape section and the 1/1 Plain weave is placed at the out of phase zig-zag stripes section, as shown in the Figure 5(a). On the other hand, in OZZF-B1 and OZZF-B2, the placement of 4/1 weave is placed at the out of phase zig-zag stripes section and the 1/1 Plain weave is placed at the central parallelogram shape section, as shown in the Figure 5(b).

To study the effect of weft yarn arrangement, two arrangements of weft yarn are used to fabricate the designed single layered fabrics. In the first arrangement which is named as (1R, 1L), alternate elastic and non-elastic yarns are used to produce fabrics OZZF-A1 and OZZF-B1. In the second arrangement named as (L), only elastic yarns are used to produce fabrics OZZF-A2 and OZZF-B2. The specifications of all the developed fabrics are presented in Table 1. Moreover, to create differential shrinkage along weft direction and warp direction, elastic and non-elastic yarns have to be used alternately. This require a weaving machine with more than one supplies of weft as well as warp yarns. Therefore, the rapier weaving machine manufactured by CCI Intech Taiwan with option of eight weft supplies, dobby shedding mechanism and second beam assembly attachment was used to weave bi-stretch auxetic woven fabrics based on foldable geometries. The core spun spandex cotton yarn of linear density 14.8 Tex with a core of 4.44 Tex spandex filament and spun cotton yarns of linear density 14.8 Tex are used as elastic and non-elastic yarns, respectively. The Young's modulus of elastic yarn is 10MPa and of non-elastic yarn is 30MPa. It is important to mention that both the yarns have positive Poisson's ratio. The woven fabrics obtained are then subjected to a hot washing for about 45 minutes with warm water (40-45°C) followed by drying at room temperature. After washing and drying, the fabrics are relaxed for 24 hours to facilitate the creation of the differential shrinkage effect of elastic and non-elastic yarn into woven fabric structure and to realize the shapes of foldable geometries. The tensile tests are then conducted on INSTRON 5566 following the testing conditions, specimen size and marking of specimen to measure tensile and transverse strain as reported by Zulifqar et al. [31, 34]. The tensile testing process is video recorded using a high-resolution camera (Canon EOS 800D). The video resolution used is Full HD (1920 x 1080). The photographs are then extracted with a time interval of 3s or after each 1% extension. The obtained photos of fabric are analyzed to observe the change in transverse dimensions of the fabric using a screen ruler for both the unstretched state and stretched state. The Poisson's ratio is then calculated using the following equation.

$$\nu = -\frac{\varepsilon_t}{\varepsilon_a}$$

Where ν is the Poisson's ratio (PR), ε_a is the tensile strain, and ε_t is the transversal strain.

3. Results and discussion

3.1. Realization of auxetic geometrical structure and NPR effect of double layered fabric

Figure 6 shows the face and back of the double layered fabric after relaxation. It is observed that upon relaxation, the elastic warp yarns in the back layers make the fabric to collapse in the warp direction and elastic weft yarns in the face layer makes the fabric to collapse in the weft direction. Because the two fabric layers are stitched and unstitched in alternate parallel in phase zig-zag manner, flats appear on the face and back of the fabric at the stitched sections, and due to higher shrinkage of elastic weft yarns in the face layer and elastic warp yarns in the back layer, the parallel in-phase zig-zag double directional folds appear on the face of the fabric at unstitched section. On the back of the fabric, at unstitched sections due to shrinkage of elastic warp yarns, the abrupt convexities are formed. Therefore, the fabric has alternate parallel in-phase zig-zag flat strips and double directional folded strips on the face of the fabric, while on the back of the fabric are alternate flat portion and abrupt convexities running along weft direction. When the fabric is extended, the folded strips on the face of the fabric and abrupt convexities on the back of the fabric are unfolded and the dimension of the whole fabric is increased resulting in NPR effect.

Figure 7 shows the Poisson's ratio versus tensile strain curves of the fabric IZZF-2, when stretched in two principal directions. It can be seen that the NPR effect is produced in both principal directions. However, a higher NPR effect is produced when the fabric is stretched along weft direction as compared to that produced along warp direction. In addition, when stretched along warp direction, the initial NPR effect is achieved at higher tensile strains as compared to that achieved along weft direction. The reason for this behavior is that upon stretch along warp direction, the initial stretching force is disbursed in the opening of the abrupt convexities on the back of the fabric and the opening of parallel zig-zag folds on the face of the fabric happens only after complete opening of the abrupt convexities at the back of the fabric. Therefore, the opening of zig-zag folds on the face of the fabric is delayed and occurs at higher tensile strains resulting in smaller initial NPR effect at higher tensile strain. On the other hand, when stretched along weft direction, the opening of zig-zag folds on the face of the fabric is initiated at initial tensile strains resulting in higher initial NPR as shown in Figure 7.

3.2. Realization of auxetic geometrical structure and NPR effect of single layered fabric

In case of single layered fabrics, upon relaxation, the differential shrinkage effect created by combinations of loose weave and tight weave along with elastic and non-elastic yarns, makes the fabric structural unit cell to occupy a non-uniform contraction/shrinkage profile. Therefore, the loose weave sections undergo higher shrinkage and tight weave sections undergo lesser shrinkage, making the face and back of the fabric to obtain different appearance. Figures 8-9 show the face and back of the produced typical fabrics OZZF-A1 and OZZF-B1, respectively.

It can be seen from the fabric photos that the warp yarns and weft yarns are prominent at loose weave sections because of long floats of warp and weft yarns on the face and back of the fabric respectively. In addition, the warp yarns and weft yarns become narrower at these sections, and the fabric is flat and thicker because of swelling of yarn due to shortening of yarn length which is instigated by higher shrinkage of elastic yarns in two directions. Therefore, at loosely woven sections, the warp and weft yarns deviate from the positions they held at tightly woven sections and came closer. On the other hand, at tight weave sections, the warp and weft yarns are not as mobile as in loose weave sections, and due to higher shrinkage of loose weave sections, the tightly woven sections collapse and occupy a bulged or folded form. Hence, folds or bulges are created between loosely woven sections. Moreover, the extent of folded effect or height of bulge is different for both fabrics. In case of fabric OZZF-A1, the folds are created at out of phase tightly woven zig-zag sections, while in case of fabric OZZF-B1, the bulges are created at the tightly woven parallelogram sections between loosely woven out of phase zig-zag sections.

Upon stretching along either direction, the fabrics undergo tensile deformation and the folded areas are opened, making them to expand in the transverse direction and produce NPR. Figures 10-11 show the Poisson's ratio versus tensile strain curves for two single layered fabrics OZZF-A1 and OZZF-B1, respectively, when stretched in warp and weft direction. The fabric OZZF-A1, when stretched in warp direction yields a NPR value of -0.26 at a tensile strain of 4%, which decreases to -0.20 up to a tensile strain of 8%. The NPR falls in the range of -0.10 to -0.15 at tensile strain of 9-80%. When this fabric is stretched in weft direction, a smaller NPR of -0.07 is achieved at a tensile strain of 13% and decreases to -0.05 at a tensile strain of 79%, as shown in Figure 10. The fabric OZZF-B1, when stretched along warp direction, produces NPR values of -0.17 at a tensile strain of 7% and -0.1 to -0.12 up to a tensile strain of 85%. When stretched along weft direction, the NPR of -0.1 is achieved at a tensile strain of 6%, as shown in Figure 11. It can be seen that in case of both fabrics, the NPR is produced in both stretch directions. Figures 10-11 also show that the NPR effect of the fabric reaches its highest level at low tensile strains and then reduces with increasing tensile strains. In addition, the NPR effect when stretched in the warp direction is higher for both fabrics than that when stretched in the weft direction. This is because due to the placement of loose weave stripes along weft direction, higher folded effect and extensibility is achieved along weft direction as compared to that achieved along warp direction. Therefore, upon stretch along weft direction, because of the higher extensibility along this direction and smaller folded effect along warp direction, smaller opening of the folded area along transverse direction (warp direction) is achieved at higher tensile strains resulting in smaller NPR effect. On the other hand, when the fabric is stretched along the warp direction, due to the smaller folded effect and extensibility along this direction and larger folded effect along weft direction, larger opening of the folded area along the transverse direction (weft direction) is achieved even at smaller tensile strains resulting in higher NPR effect.

To explain the mechanism of tensile deformation of single layered fabrics, Figure 12(a) shows an approximation of the fabric at unstretched state with a tightly woven folded or bulged section (solid lines) and the yarns at loosely woven sections (dashed lines). They are shown free of interlacements just to make the explanation clear. The mechanism of tensile deformation involves three phases as illustrated in the Figure 12. In the first phase upon stretching in any direction, the yarn shrinkage at loose weave sections is rearranged and the tensile yarns tend to get straight, as shown in Figure 12(b). This is followed by opening of folded areas in the transverse direction immediately at lower tensile strains, that is why a higher initial NPR effect is produced. In the second phase, the yarns shift towards the position which they held at the tight weave sections by moving apart from each other, as shown in Figure 12(c). This increases the values of tensile strain and the NPR effect starts to decrease.

In the third phase, once the shift is achieved, the tensile yarns at the tight weaves sections move towards straight form and the yarns in the transversal direction also experience a persuasive frictional force due to frictional binding forces between the yarns at the cross-over points and tend to get straight, as shown in Figure 12(d). Therefore, the yarn system becomes more ordered and a more consolidated orientation (straight orientation) is achieved. This straightening of the tensile and transversal yarns continues and open the fold or bulge in transverse direction which increases the transverse dimension of the fabric giving rise to the NPR effect. After the maximum opening is achieved, the further increase in the transverse dimension is restricted and the tensile force is consumed by increasing the tensile strain. Therefore, the NPR effect starts to decrease because of the increasing tensile strain. This behavior is continued until the frictional forces at the crossover points are overcome and the yarns slip over each other after which the fabric behaves conventionally. Therefore, the stretching force is consumed in straightening of tensile yarns at loose weave sections, followed by the shifting of yarns from closer to apart from each other, followed by opening of fold or bulge until the slippage point is reached.

3.2.1. Effect of loose weave placement on NPR effect of single layered fabrics

Figures 13-14 show the comparison of NPR effect produced by two fabrics OZZF-A1 and OZZF-B1 with different placement of loose weave, when stretched in warp and weft direction respectively. When stretched along warp direction, a higher initial NPR effect is produced by the fabric OZZF-A1 as compared to that produced by the fabric OZZF-B1. The NPR effect decreases rapidly up to a tensile strain of 15% and then increases again. On the other hand, in case of fabric OZZF-B1, a smaller NPR effect is produced initially and decreases up to a tensile strain of 25%. It can also be seen that above a tensile strain of 25%, the NPR behavior of both fabrics is almost similar. When the fabrics are stretched along weft direction, the fabric OZZF-B1 produces initial NPR effect below a tensile strain of 10 % but the fabric

OZZF-A1 produces initial NPR over a tensile strain of 10%. The NPR effect of both fabrics decreases rapidly up to a tensile strain of 30%. After that, the NPR effect of both fabrics becomes similar up to a tensile strain of 60%. After that the NPR of fabric OZZF-A1 continue to decrease but the NPR effect of fabric OZZF-B1 is kept almost constant. One obvious reason for different behavior is the different placement of loose weave within the unit cell of both fabrics. In fabric OZZF-A1, the 4/1 loose weave is placed at the central parallelogram shape section, while the 1/1 Plain weave is placed at the parallel out of phase zig-zag section, as shown in Figure 15(a). On the other hand, in fabric OZZF-B1, the placement of 4/1 loose weave and 1/1 Plain weave is opposite to that of fabric OZZF-A1, as shown in Figure 15(b). Therefore, upon relaxation, the yarns in the loose weave sections undergo higher shrinkage and force the tight weave sections to collapse differently in case of two fabrics.

In case of fabric OZZF-A1, the higher shrinkage of central loose weave section makes the exterior parallel out of phase zig-zag tight weave sections to collapse and creates folded effect, as shown in Figure 15(a). On the other hand, in case of fabric OZZF-B1, the exterior parallel out of phase zig-zag loose weave section undergoes higher shrinkage and forces the central tight weave section to collapse and creates bulges, as shown in Figure 15(b). However, the folded effect is more in case of OZZF-A1, because the area of loose weave section is larger than the area of tight weave section, therefore, the higher shrinkage of yarns in larger area is utilized in collapsing of the tight weave sections. On the contrary, in case of fabric OZZF-B1, the area of loose weave section is smaller and maximum yarn shrinkage is accommodated within the loose weave section, making the yarns to swell and the fabric become thicker at these sections. That is why a larger folded effect is observed in case of fabric OZZF-A1, especially along weft direction. Conversely, in case of fabric OZZF-B1, more thick lines at the loose weave sections, and slight bulges at the tight weave central section are observed. Therefore, upon stretch along warp direction, because of larger folded effect along transverse direction larger initial opening of folded sections is achieved, resulting in higher initial NPR effect. When stretched along weft direction, because of larger folded effect and extensibility along this direction in case of fabric OZZF-A1, the opening of folded sections is delayed and occurs at higher tensile strain. That is why the initial NPR effect is produced at higher tensile strains by this fabric as compared to the fabric OZZF-B1.

3.2.2. Effect of weft yarn arrangements on NPR effect of single layered fabrics

Figures 16-19 show a comparison of NPR effect produced by the fabrics with different weft yarn arrangements when stretched along warp and weft directions respectively. When stretched along warp direction, the NPR effect of both fabrics OZZF-A2 and OZZF-B2 with all elastic yarns in weft is reduced and produced at higher tensile strains, as compared to that produced by the fabrics OZZF-A1 and OZZF-B1 with alternate elastic yarns in weft, as shown in Figures 16-17. When stretched along weft direction, the initial NPR effect is increased for both fabrics OZZF-A2 and OZZF-B2 with all elastic yarns in weft, as shown in Figure 18-19. In case of fabric OZZF-A2, the initial NPR effect is rapidly decreased and continues to decrease with increasing tensile strain. In case of fabric OZZF-B2, the initial NPR effect decreases with increasing tensile strain. However, a larger NPR effect is produced by this fabric up to a tensile strain of 60% than that produced by the fabric with alternate elastic yarns in weft.

This behavior can be explained by the fact that in case of the fabric OZZF-A2 with all elastic yarns in weft, the differential shrinkage and folded effect along weft direction is increased, because of larger loosely woven area at the central parallelogram section and all elastic yarns in weft. Therefore, upon stretch along weft direction, the opening of folded effect along warp direction is achieved initially but is further restricted by the higher folded effect and extensibility along this direction. This results in higher initial NPR effect which decreases with increasing tensile strain, as shown in Figure 18. When this fabric is stretched along warp direction, the opening of larger folded sections is restricted by the higher shrinkage at loosely woven central parallelogram section and occurs only at higher tensile strain which results in smaller NPR effect at higher tensile strains, as shown in Figure 16. On the other hand, in case of the fabric OZZF-B2 with all elastic yarns in weft, the differential shrinkage effect is minimized, because the maximum shrinkage is accommodated within the smaller loosely woven out of phase zig-zag section, resulting in smaller bulge formation along weft direction at the central parallelogram section, and the larger bulges are formed only along warp direction. Therefore, upon stretch along weft direction, the larger bulges along warp direction are opened, causing higher NPR effect, as shown in Figure 19. Conversely, when the fabric is stretched along warp direction, the opening of smaller bulges along weft direction results in smaller NPR effect, as shown in Figure 17. Notably, all the fabrics exhibit NPR effect up to a tensile strain of above 100%.

4. Conclusions

This study reports the development of bi-stretch auxetic woven fabrics based on foldable geometrical structures using elastic and non-elastic yarns and conventional weaving machinery. The phenomenon of differential shrinkage is successfully created to realize parallel in-phase zig-zag foldable structure into double layered woven fabric and out of phase zig-zag foldable structure into single layered woven fabric. In addition, two variations of single layered fabric are also produced with two different weft yarns arrangements and the effect of weft yarn arrangements is studied. All the fabrics exhibit NPR effect over a larger strain range. From the study, the following conclusions can be obtained.

1. Double layered auxetic woven fabrics based on parallel in phase zig-zag foldable geometrical structure can produce NPR effect in both principle directions. However, it is higher when the fabric is stretched along weft direction than when stretched along

warp direction. This behaviour is different from the results obtained for single layer fabrics.

2. The parallel in phase zig-zag foldable geometrical structure is capable of inducing auxetic behavior into double layered auxetic woven fabrics due to creating non-uniform contraction profiles within the unit cell of fabric structure.
3. Out of phase zig-zag foldable geometrical structure can produce NPR effect and can be realized into single layered fabric by exploiting the phenomenon of differential shrinkage.
4. Single layered bi-stretch auxetic woven fabrics based on out of phase zig-zag foldable structure produces NPR effect in both principle directions but higher NPR effect is achieved when the fabric is stretched along warp direction than when stretched along weft direction.
5. In single layered bi-stretch auxetic woven fabrics based on out of phase zig-zag foldable structure, the placement of loose weave at the central parallelogram section can produce larger folded effect and higher initial NPR at smaller strains.
6. In single layered bi-stretch auxetic woven fabrics based on out of phase zig-zag foldable structure, using all elastic yarns in weft direction increases the NPR effect along weft direction but decreases the NPR effect along warp direction.

Acknowledgement

The authors would like to thank the funding support from the Research Grants Council of Hong Kong Special Administrative Region Government (grant number: 15209616).

References

[1]. R. Lakes, *Science* **1987**, *235*, 1038.

[2]. K. W. Wojciechowski, *Phy. Lett A* **1989**, *137*, 60.

[3]. K.E. Evans, A. Alderson, *Advanced Materials* **2000**, *12*, 617.

[4]. K. Evans, M. Nkansah, I. Hutchinson, S. Rogers, *Nature 1991*, *53*, 124.

[5]. Z. Wang, A. Zulifqar, H. Hu, in *Advanced Composite Materials for Aerospace Engineering: Processing, Properties and Applications*, Vol. 1 (Eds: R. Sohel, F. Raul), Woodhead Publishing, Cambridge, UK **2016**, pp. 213-240.

[6]. L. Zhou, L. Jiang, H. Hu, *Phys. Status Solidi B* **2016**, *253*, 1233.

[7]. F. Steffens, S. Rana, R. Fangueiro, *Mater. Des.* **2016**, *106*, 81.

[8]. L. Jiang, B. Gu, H. Hu, *Composite Structures* **2016**, *135*, 23.

[9]. A. Bezazi, F. Scarpa, *Int. J. Fatigue* **2007**, *29*, 922.

[10]. F. Scarpa, F. Smith, *J. Intell. Mater. Syst. Struct.* **2004**, *15*, 973.

[11]. N. Chan, K. Evans, *J. Cell. Plas.* **1998**, *34*, 231.

[12]. G. Imbalzano, P. Tran, T.D. Ngo, P.V. Lee, *Composite Structures* **2016**, *135*, 339.

[13]. K. K. Dudek, W. Wolak, R. Gatt, J. N. Grima, *Sci. Rep.* **2019**, *9*, 3963.

[14]. Z. Wang, H. Hu, *Text. Res. J.* **2017**, *87*, 1925.

[15]. R.H. Baughman, J. M. Shacklette, A. A. Zakhidov, S. Stafström, *Nature* **1998**, *392*, 362.

[16]. J. Clarke, R. Duckett, P. Hine, I. Hutchinson, I. Ward, *Composites* **1994**, *25*, 863.

[17]. S. Hirotsu, *J. Chem. Phys.* **1991**, *94*, 3949.

[18]. P.M. Pigłowski, K. W. Wojciechowski, K. V. Tretiakov, *Phys. Status Solidi RRL* **2016**, *10*, 566.

[19]. K. V. Tretiakov, P.M. Pigłowski, K. Hyżorek, K. W. Wojciechowski, *Smart Mater. Struct.* **2016**, *25*, 054007.

[20]. Y.T. Yao, K. L. Alderson, A. Alderson, *Cellulose* **2016**, *23*, 3429.

[21]. K. Alderson, K. Evans, *Polymer* **1992**, *33*, 4435.

[22]. A. Alderson, K. E. Evans, *J. Mater. Sci.* **1995**, *30*, 3319.

[23]. G. W. Milton, *J. Mech. Phys. Solids* **1992**, *40*, 1105.

[24]. J. Choi, R. Lakes, *J. Compos. Mater.* **1995**, *29*, 113.

[25]. K. Alderson, A. Alderson, G. Smart, V. Simkins, P. Davies, Plast., Rubber Compos. **2002**, *31*, 344.

[26]. M. Sloan, J. Wright, K. Evans, *Mech. Mater.* **2011**, *43*, 476.

[27]. J. R. Wright, M. K. Burns, E. James, M. R. Sloan, K. E. Evans, *Text. Res. J.* **2012**, *82*, 645.

[28]. Z. Ge, H. Hu, S. Liu, *J. Text. Inst.* **2016**, *107*, 578.

[29]. T. C. Lim, *Phys. Status Solidi B* **2014**, *251*, 273.

[30]. W.S. Ng, H. Hu, *Phys. Status Solidi B* **2017**, *254*, 1600790.

[31]. A. Zulifqar, H. Hu, *Phys. Status Solidi B* **2019**, *256*, 1800172.

[32]. A. Zulifqar, H. Hu, *Text. Res. J.* 2019, 0040517519836936.

[33]. H. Cao, A. Zulifqar, T. Hua, H. Hu, *Text. Res. J.* **2019**, *89*, 2694.

[34]. A. Zulifqar, T. Hua, H. Hu, *Text. Res. J.* **2018**, *88*, 2076.

[35]. H. Kamrul, A. Zulifqar, H. Hu, *Text. Res. J.* **2019**, 0040517519869391.

[36]. V. Monika, V. Petra, *J. Donghua Univ.* **2013**, *5*, 71.

[37]. W. S. Ng, H. Hu, *Polymers* **2018**, *10*, 226.

[38]. M. Glazzard, P. Breedon, *Phys. Status Solidi B* **2014**, *251*, 267.

[39]. S. C. Ugbolue, Y. K. Kim, S. B. Warner, Q. Fan, C.-l. Yang, O. Kyzymchuk (University of Massachusetts.), U.S. patent *8772187*, **2014**.

[40]. H. Hu, Z. Wang, S. Liu, *Text. Res. J.* **2011**, *81*, 1493.

[41]. S. C. Ugbolue, Y. K. Kim, S. B. Warner, Q. Fan, C. L. Yang, O. Kyzymchuk, Y. Feng, J. Lord, *J. Text. Int*. **2011**, *102*, 424.

[42]. Y. Liu, H. Hu, J. K. Lam, S. Liu, *Text. Res. J.* **2010**, *80*, 856.

[43]. S. C. Ugbolue, Y. K. Kim, S. B. Warner, Q. Fan, C.-L. Yang, O. Kyzymchuk, Y. Feng, *J. Text. Int.* **2010**, *101*, 660.

[44]. Z. Wang, H. Hu, *Text. Res. J.* **2015**, *85*, 404.

[45]. Z. Wang, H. Hu, *Phys. Status Solidi B* **2014**, *251*, 281.

[46]. Z. Wang, H. Hu, X. Xiao, *Text. Res. J.* **2014**, *84*, 1361.

[47]. K. Alderson, A. Alderson, S. Anand, V. Simkins, S. Nazare, N. Ravirala, *Phys. Status Solidi B* **2012**, *249*, 1322.

[48]. Z. Ge, H. Hu, Y. Liu, *Smart Mater. Struct*. **2013**, *22*, 84005.

[49]. Z. Ge, H. Hu, *Text. Res. J.* **2013**, *83*, 543.

[50]. P. Verma, M. L. Shofner, A. Lin, K. B. Wagner, A. C. Griffin, *Physica Status Solidi B* **2015**, *252*, 1455.

[51]. H. Hu and A. Zulifqar, *J Textile Eng Fashion Technol.* **2016**, *1*, 00002.

[52]. N. Gokarneshan, *Fabric structure and design.* New Age International Publishers, New Delhi **2004**, p.7.

[53]. Z. Wang, H. Hu, *Text. Res. J.* **2014**, *84*, 1600.

[54]. Y. Prawoto, *Comput. Mater. Sci.* **2012**, *58*, 140-153.

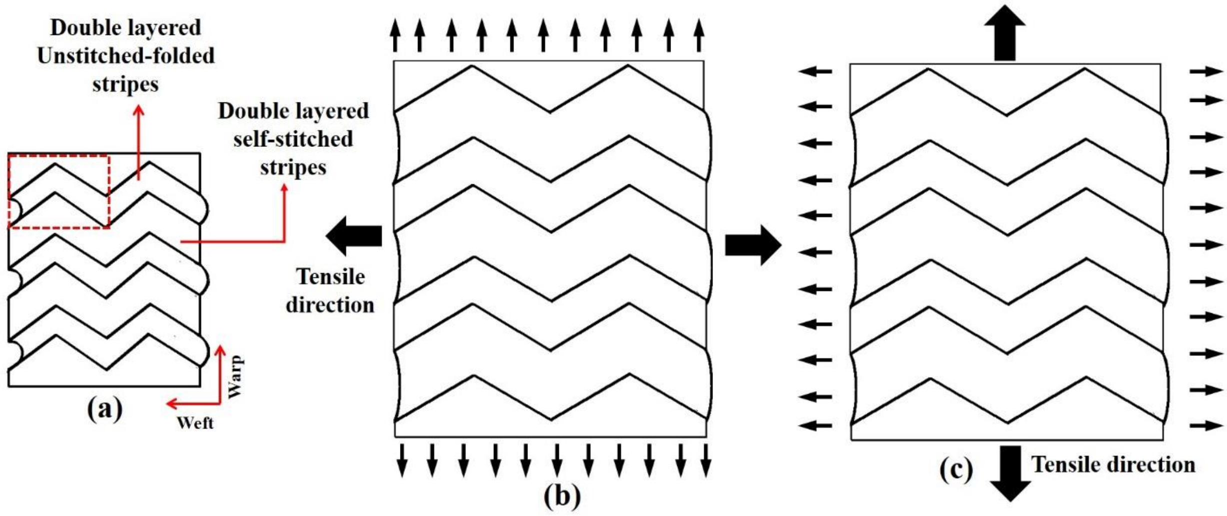

Figure 1. Foldable geometry with parallel in phase zig-zag stripes used for double layered fabric: (a) unstretched state; (b) stretched along weft direction; (c) stretched along warp direction.

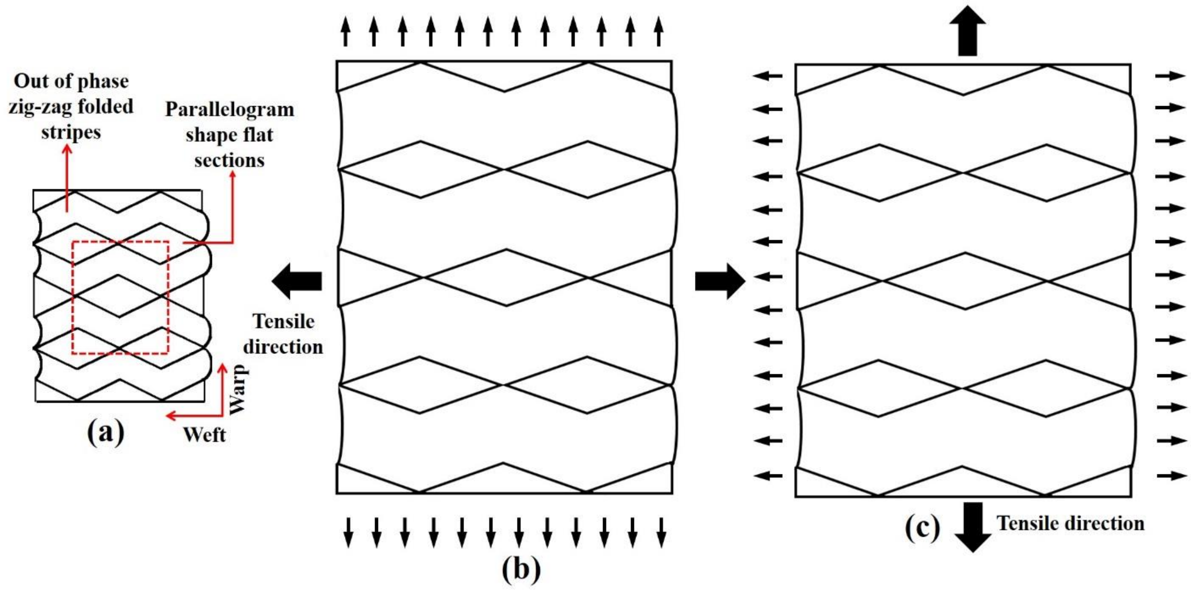

Figure 2. Foldable geometry with parallel out of phase zig-zag folded stripes used for single layered fabric: (a) unstretched state; (b) stretched along weft direction; (c) stretched along warp direction.

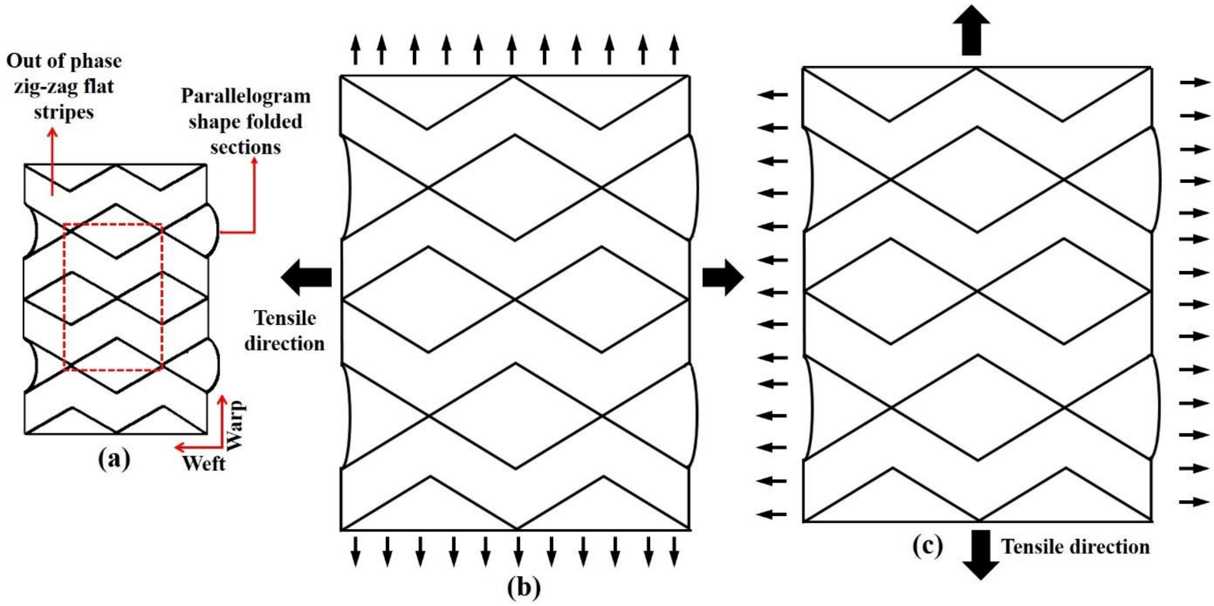

Figure 3. Foldable geometry with parallel out of phase zig-zag flat stripes used for single layered fabric: (a) unstretched state; (b) stretched along weft direction; (c) stretched along warp direction.

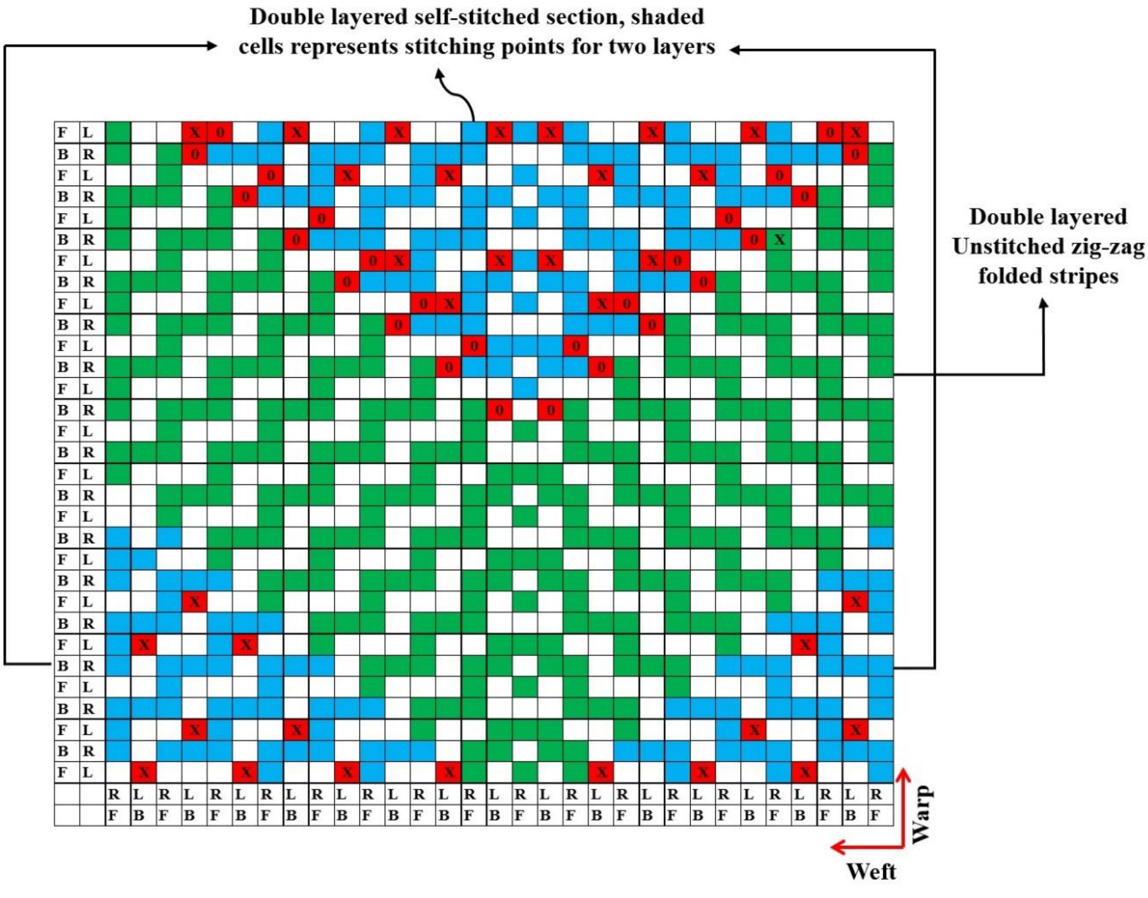

Figure 4. Interlacement pattern for double layered fabric based on parallel in-phase zig-zag foldable strips.

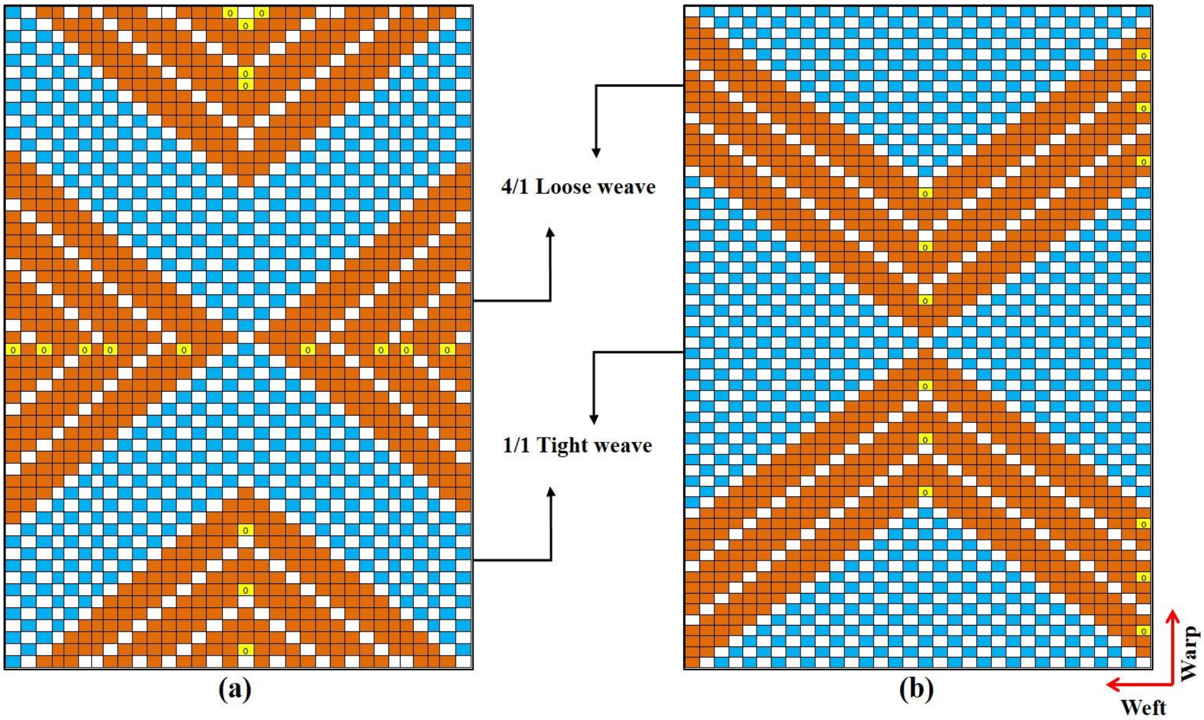

Figure 5. Interlacement patterns of single layered fabrics: (a) fabric with out of phase folded stripes OZZF-A1 and OZZF-A2; (b) fabric with out of phase flat stripes OZZF-B1 AND OZZF-B2.

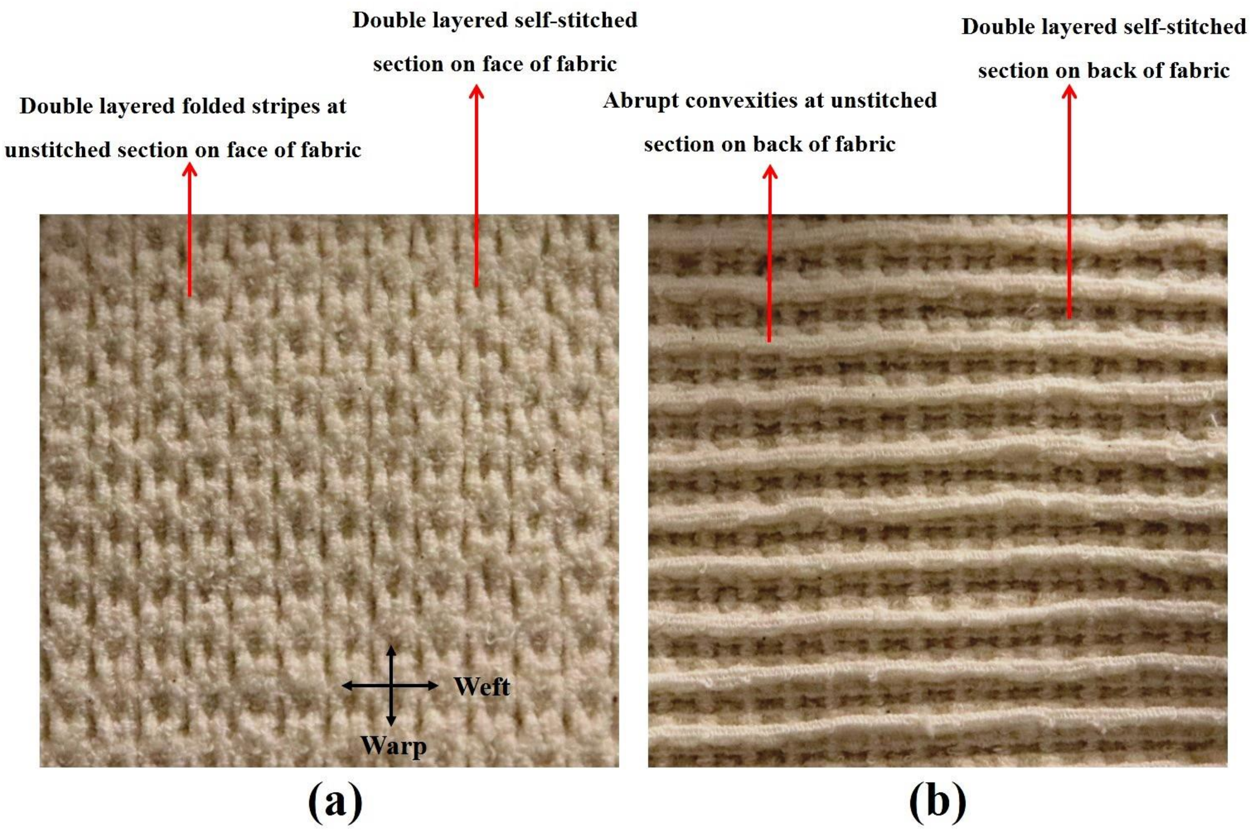

Figure 6. Double layered fabric (IZZF2) with parallel in-phase zig-zag folds: (a) fabric face; (b) fabric back.

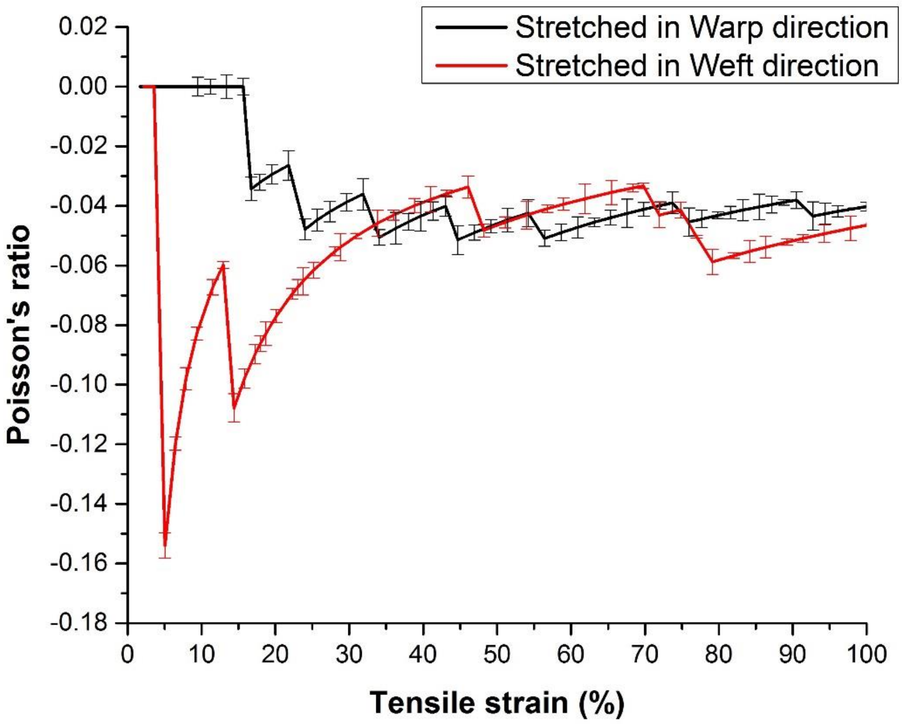

Figure 7. Poisson's ratio versus tensile strain curves of fabric IZZF-2

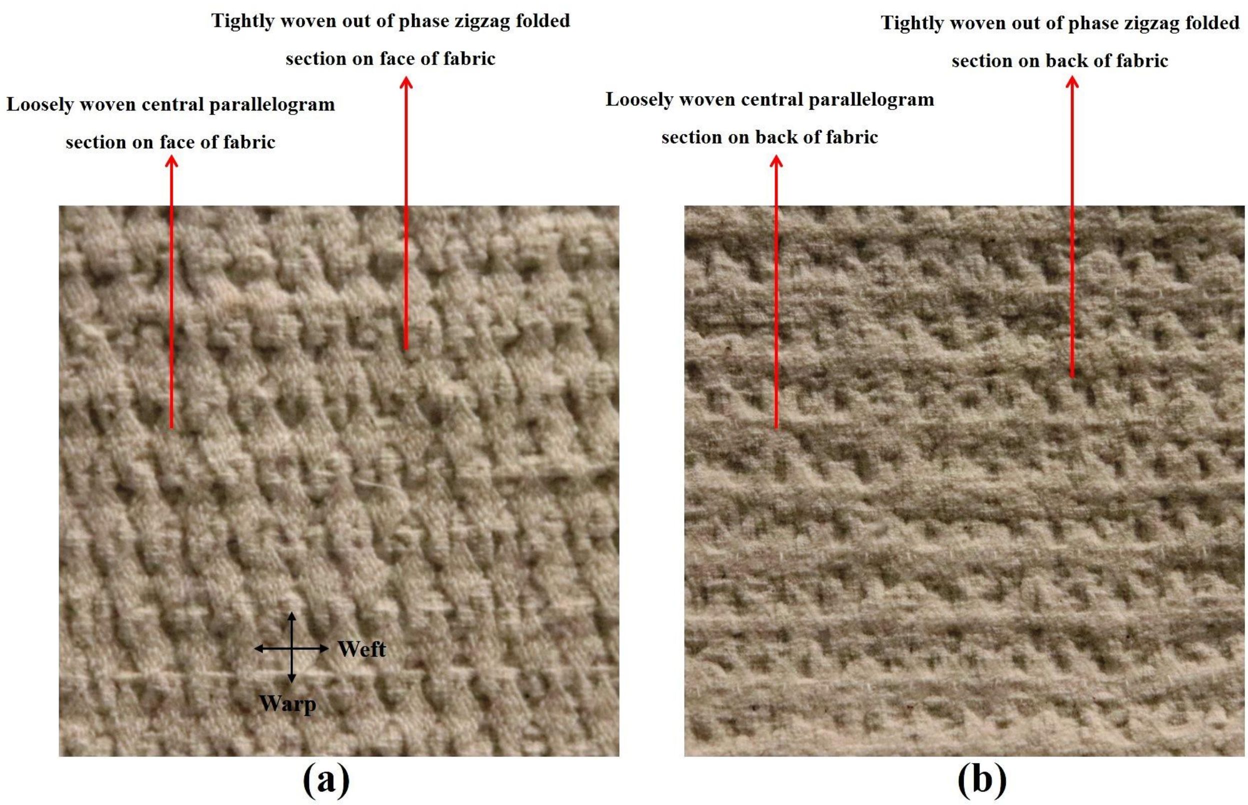

Figure 8. Single layered fabric OZZF-A1: (a) fabric face; (b) fabric back.

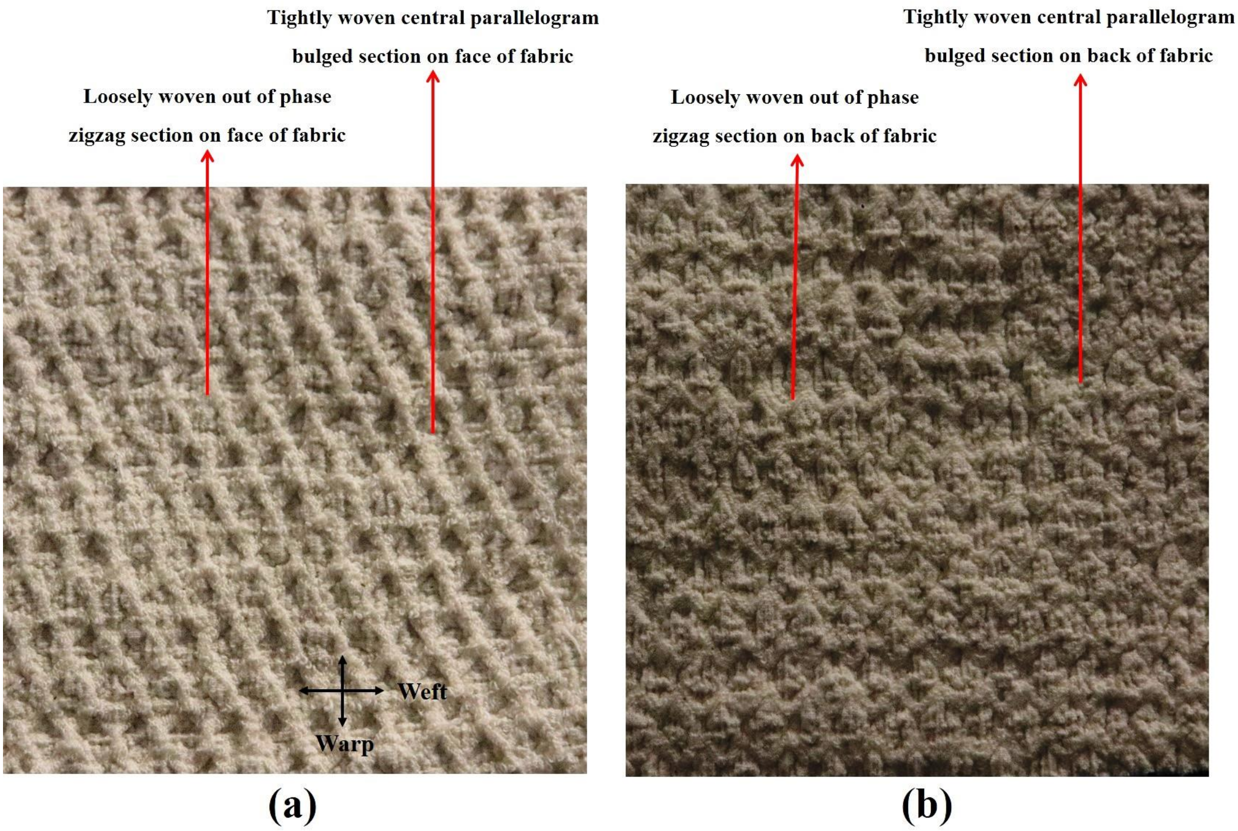

Figure 9. Single layered fabric OZZF-B1: (a) fabric face; (b) fabric back.

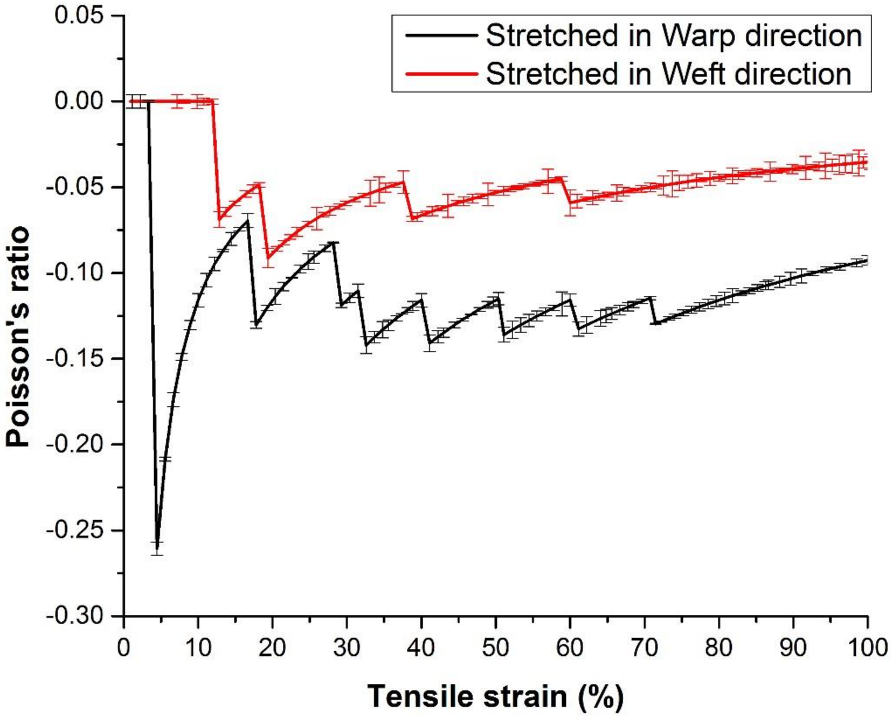

Figure 10. Poisson's ratio versus tensile strain curves of fabric OZZF-A1.

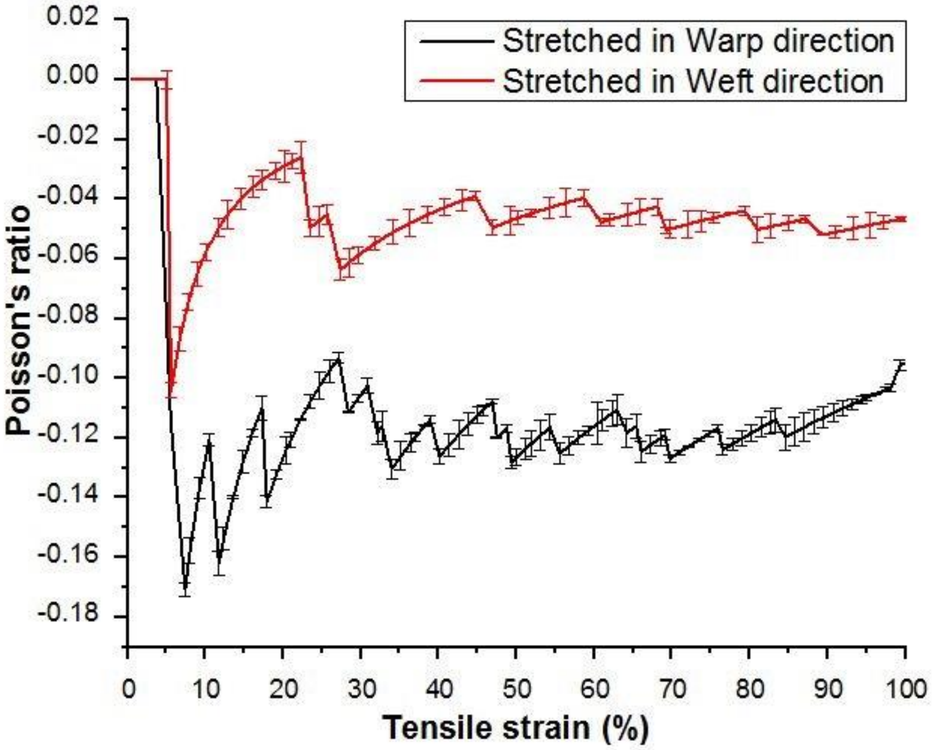

Figure 11. Poisson's ratio versus tensile strain curves of fabric OZZF-B1.

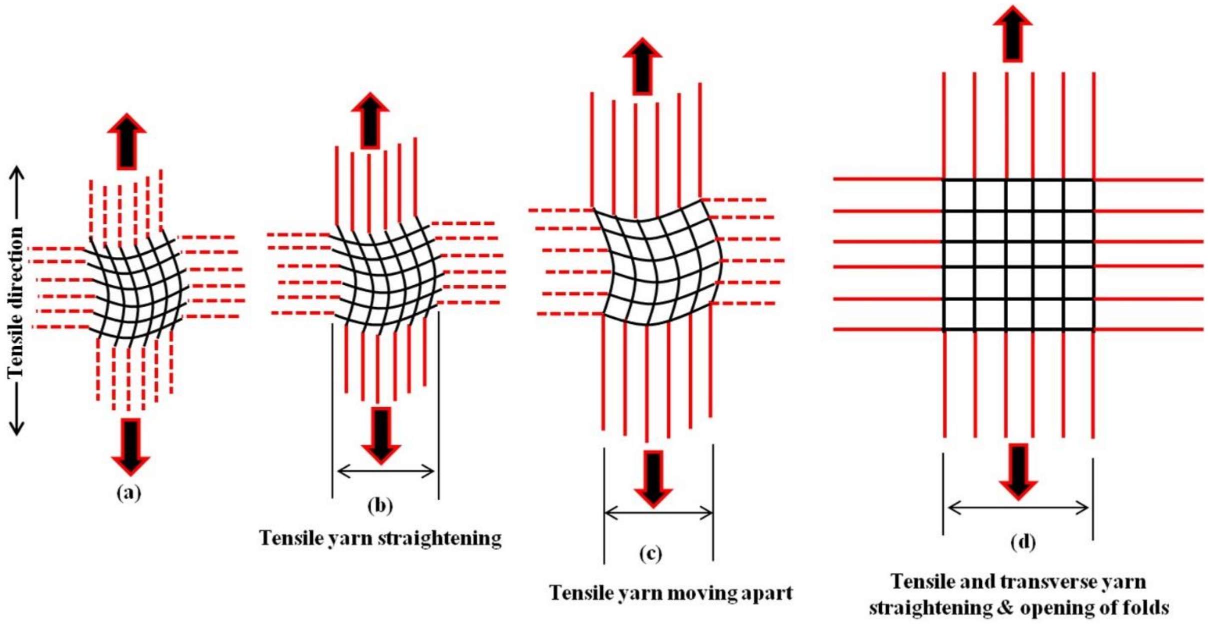

Figure 12. Deformation mechanism: (a) relaxed state; (b) phase-1; (c) phase-2 (d) phase-3.

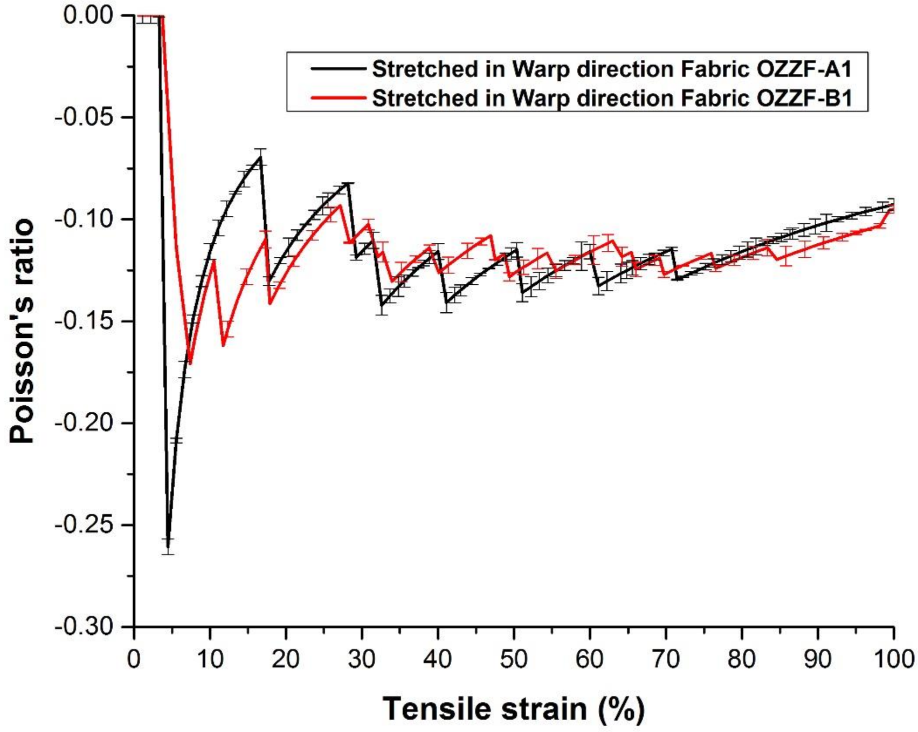

Figure 13. Poisson's ratio versus tensile strain curves of fabrics when stretched along warp direction.

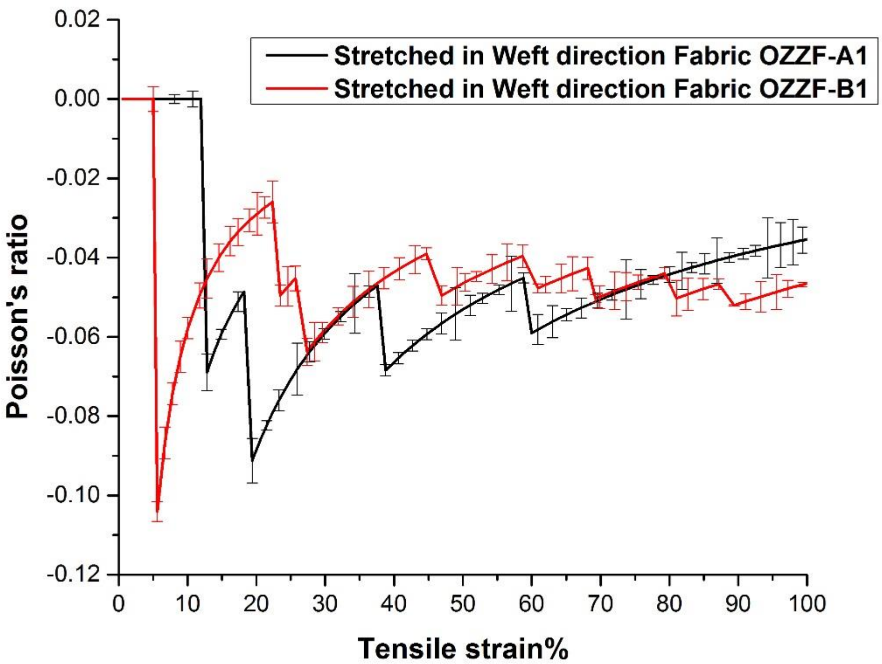

Figure 14. Poisson's ratio versus tensile strain curves of fabrics when stretched along weft direction.

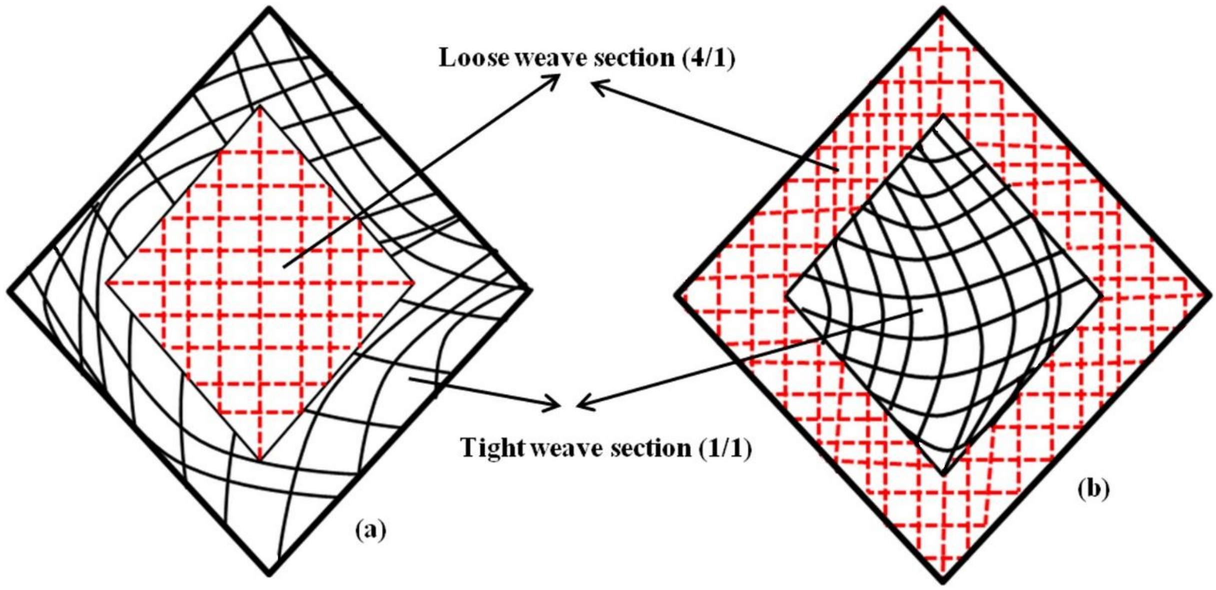

Figure 15. Illustration of loose weave and tight weave placement: (a) OZZF-A1; (b) OZZF-B1.

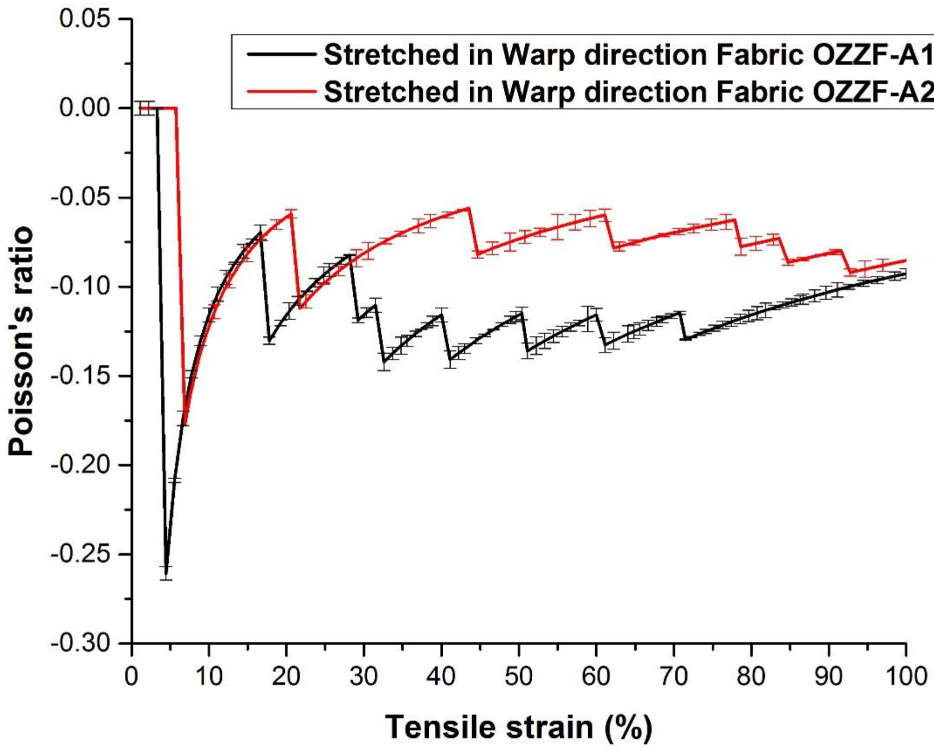

Figure 16. Poisson's ratio versus tensile strain curves of fabrics with two different weft yarn arrangements when stretched along warp direction.

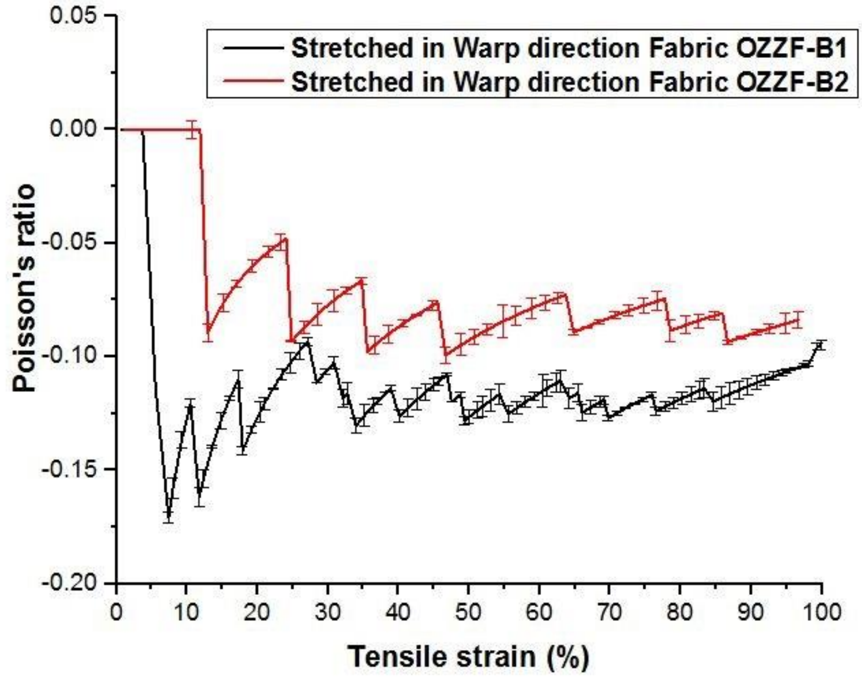

Figure 17. Poisson's ratio versus tensile strain curves of fabrics with two different weft yarn arrangements when stretched along warp direction.

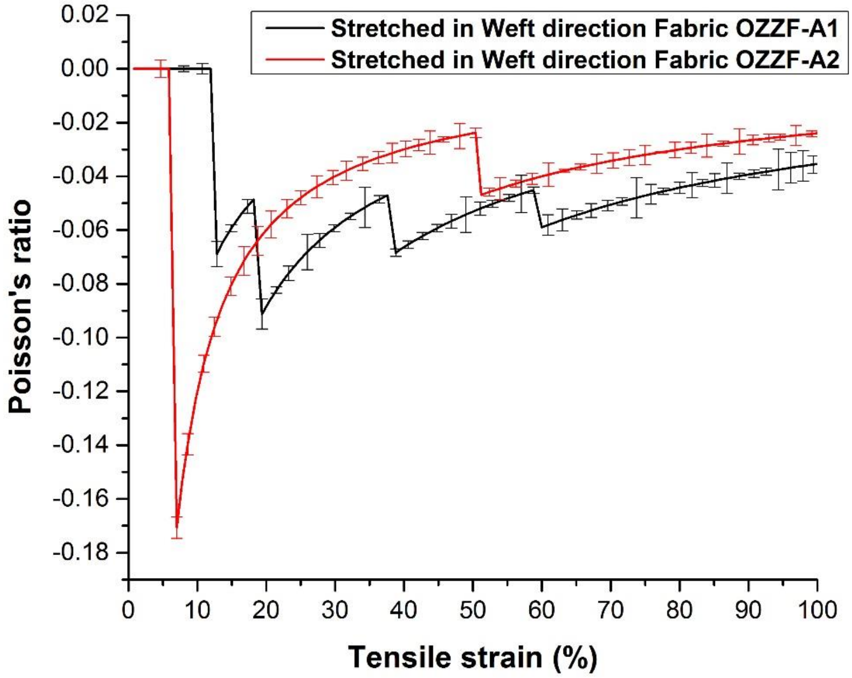

Figure 18. Poisson's ratio versus tensile strain curves of fabrics with two different weft yarn arrangements when stretched along weft direction.

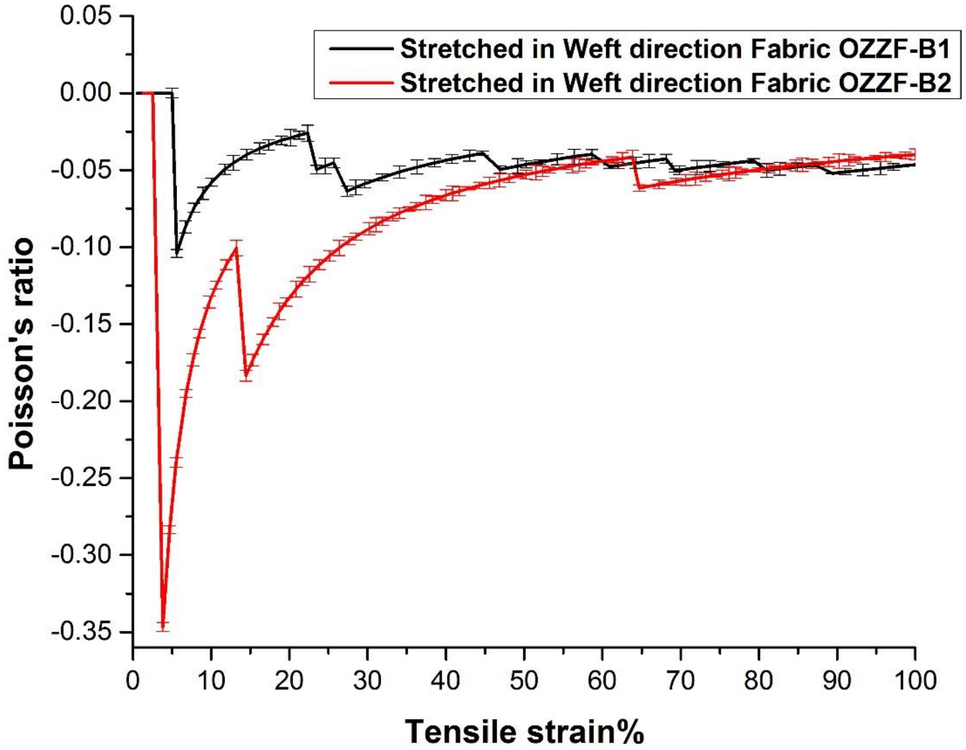

Figure 19. Poisson's ratio versus tensile strain curves of fabrics with two different weft yarn arrangements when stretched along weft direction.

Table 1. Specifications of the developed fabrics

Fabric ID	OZZF-A1	OZZF-B1	OZZF-A2	OZZF-B2	IZZF-2
No of layers	1				2
Warp yarn arrangement	1R,1L				1R,1L
Weft yarn arrangement	1R,1L		(L)		1R,1L
Warp yarn density	25.19/cm				--
Weft yarn density	23.62/cm				--

R = Non-elastic yarn, L = Elastic yarn