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Bi-stretch auxetic woven fabrics based on foldable geometry

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Abstract:

The fabrication of auxetic fabrics by using conventional yarns and machinery has gained the extraordinary interest of researchers in recent years. However, so far this approach is only adopted to fabricate auxetic knitted fabrics and uni-stretch auxetic woven fabrics. This paper reports a study of developing a new class of bi-stretch woven fabrics with auxetic behavior by using conventional elastic and non-elastic yarns and available weaving machinery. Bi-stretch auxetic woven fabrics were firstly designed based on a foldable geometry possessing negative Poisson's ratio by consideration of different design parameters including the yarn float length, placement of tight and loose weaves and arrangement of elastic and non-elastic yarns in weft direction, and then fabricated on a dobby weaving machine equipped with multiple weft supplies and a separately controlled second beam assembly attachment. The fabricated fabrics were finally tested on a tensile machine to assess their auxetic behavior in both warp and weft directions. The results showed that the bi-stretch woven fabrics developed exhibit negative Poisson's ratio up to -0.36 and -0.27 when stretched along the warp direction and weft direction respectively and could be applied for clothing applications which require enhanced shape fit and comfort.

Key words: auxetic; bi-stretch; weaving; negative Poisson's ratio

1. Introduction

The conventional fabrics have positive Poisson's ratio (PR) and upon stretching in one direction, they undergo contraction in the transverse direction which is known as lateral shrinkage (Figure 1a). Whereas, the auxetic fabrics become wider when stretched and possess negative Poisson's ratio (NPR)[1-3] (Figure 1b). The term auxetic was derived from the Greek word (auxetos) which means "that which tends to increase" by Evans K[4]. A number of fascinating properties are linked with the auxetic behavior of auxetic fabrics, such as improved comfort and shape fitting at joint parts due to lateral expansion [5], increased porosity under stress [6], synclastic behavior for better formability [7], etc. These counterintuitive properties make auxetic fabrics attractive for many applications [8-10]. Such applications may include, the riding kits for bikers which can cast itself to different body shapes[11] and a fabric for denim products providing comfort and ability to mold and move easily in accordance with body movements[12], maternity wear[8] and stretchable chest band carriers[13]. Since the deformation behavior of the auxetic fabric will be consistent with that of the body movements, the shape fitting and comfort at joint parts will be improved.

Figure 1. Deformation behavior of different type of fabrics: (a) conventional; (b) auxetic.

The auxetic fabrics can be produced by two approaches[14, 15]. The first one is to fabricate auxetic fabrics by using auxetic fibers or yarns, and the second one is to fabricate auxetic fabrics from conventional yarns by using special geometrical arrangements, as the auxetic behavior is purely linked with the geometrical arrangements of structural units. The auxetic fabrics that have been produced and investigated include woven fabrics [6, 9, 16, 17], weft knitted fabrics [18-20], warp knitted fabrics [14, 21-25], textile structures for composite reinforcements [26-30] and non-woven fabrics [31]. Knitted fabrics, both warp and weft knitted, are mostly produced by adopting the second technique. The auxetic weft knitted fabrics based on foldable geometries [19, 20] and double arrowhead auxetic geometry [18] have been developed by various researchers. The auxetic warp knitted fabrics have also been developed based on spacer structure [21], rotational hexagonal loops [22], double arrowhead geometry [14] and re-entrant hexagonal knit structures [23-25]. Nevertheless, most of the developed auxetic knitted fabrics have certain limitations, such as high thickness, low structural stability and low elastic recovery, which restrict their use in tight garments. Furthermore, due to complicated geometrical structures, most of the auxetic knitted fabrics could not be produced on a larger scale.

The auxetic woven fabrics can be fabricated by both approaches. Up till today, most of the auxetic woven fabrics are produced based on regular interlacement patterns by directly using helix auxetic (HAY) yarn, either in warp direction (WD) or in weft direction (FD) [6, 16, 17]. Two types of auxetic woven fabrics by using HAY in FD were produced. The first one yielded an out of plane NPR and an in-plane NPR up to -0.1 only when the fabric is tested under thickness constraints [16]. In the second type, three weave patterns, namely, plain, 2/2 twill and 3/5(3) satin, were employed. The auxetic behavior of the woven fabrics with these constructions was tested by the image analysis. The analysis showed that while both the plain and twill fabrics exhibited most auxeticity, the satin woven fabric was significantly less auxetic[6]. Auxetic woven fabric made of HAY in the WD was a 2-ply plain woven narrow fabric. The fabric exhibited an in-plane NPR in a strain range of 15-40%, reaching a maximum NPR value of - 0.1 at 32% strain [17]. Recently, the use of non-auxetic yarns to produce auxetic woven fabrics based on special geometrical arrangements has also been reported [9]. The reported fabrics were uni-stretch auxetic woven fabrics based on foldable geometries by using conventional elastic and non-elastic yarns in FD. The maximum NPR value of -0.1 was achieved for these fabrics when stretched along FD. However, auxetic woven fabrics developed up till today also have some major limitations. For example, in case of auxetic woven fabrics made of HAY, the auxetic behavior of HAY yarns cannot be exploited fully due to the woven structural restrictions and auxetic behavior achieved is smaller and in one direction only. On the other hand, the auxetic woven fabrics made of non-auxetic yarns have extensibility and smaller NPR of -0.1 only along FD. Such limitations restrict their application in clothing. The auxetic woven fabrics made of conventional yarns and having high extensibility and NPR in both FD and WD, reduced thickness, and better formability that can easily be shaped into garments will have a great potential for clothing application.

This paper reports a study to develop such a type of fabrics by using readily available inexpensive conventional elastic and non-elastic yarns and available weaving machinery. The phenomenon of differential shrinkage is created to realize foldable geometry into the woven architecture and to produce auxetic fabrics with high extensibility and larger NPR in both WD and FD directions. As the fabrics have high extensibility in both WD and FD, they are named as bi-stretch fabrics.

2. Design and fabrication

2.1 Design principle and foldable geometry used

The auxetic behavior is purely linked to the geometrical shape of the fabric structural units. Therefore, the realization of geometry capable of inducing auxetic behavior into a woven structure is the key technique for the development of auxetic woven fabrics. There are many types of auxetic geometries which could possibly be realized into woven structure. The foldable geometry is one of such type which is used to develop bi-stretch auxetic woven fabrics in this study, because this geometry can be easily realized into the woven structure. The foldable structures can be unfolded when stretched in one direction, increasing the dimensions in the lateral direction, thus exhibiting auxetic behavior. The foldable structures have already been realized into uni-stretch auxetic woven fabrics by creating the phenomenon of differential shrinkage into the woven fabric structure [9]. It is reported that the creation of differential shrinkage phenomenon into woven fabric structure involves using a combination of weaves with different contraction/shrinkage properties and using elastic and non-elastic yarns. While the elastic yarns are used to induce the elasticity into the fabric structure and act as a return spring, the non-elastic yarns are used as a stabilizing component. When such fabric is relaxed, the differential shrinkage phenomenon enables the unit cell of fabric structure to occupy non-uniform contraction/shrinkage profile and the sections of fabric with the different tightness of weave undergo different levels of shrinkage and the folds are created. Upon stretch, the unfolding comes with spread of folded area not only in stretch direction, but also in transverse direction, giving rise to the NPR effect. Therefore, the auxetic effect is resulted due to the interplay between the interlacement pattern of warp and weft, different stretch properties of elastic and non-elastic yarn and the mechanism of deformation of the fabric.

However, in uni-stretch fabrics this phenomenon is created only in one direction and the geometry realized is based on creation of single direction folds. Therefore, these fabrics have auxetic behavior only in one direction. To achieve the auxetic effect in both directions, it is required to realize the double directional folds with the ability of spreading in two directions upon stretch. This can be achieved by creating the phenomenon of differential shrinkage in both WD as well as FD. As shown in Figure 2(a), the architecture of the foldable geometry used in this study consists of alternate double directional folded stripes and flat stripes placed in parallel in-phase zig-zag fashion running along FD with a connecting angle of 45°, which allows the design of symmetric interlacement pattern. The minimal repeating unit or unit cell of geometry is highlighted in Figure 2(b). When this double directional folded structure is subjected to an extension in either direction, the structure also expands in lateral or transversal direction due to the spreading or opening of double directional folded sections in two directions, resulting in NPR effect as shown in Figure 2(c) and 2(d).

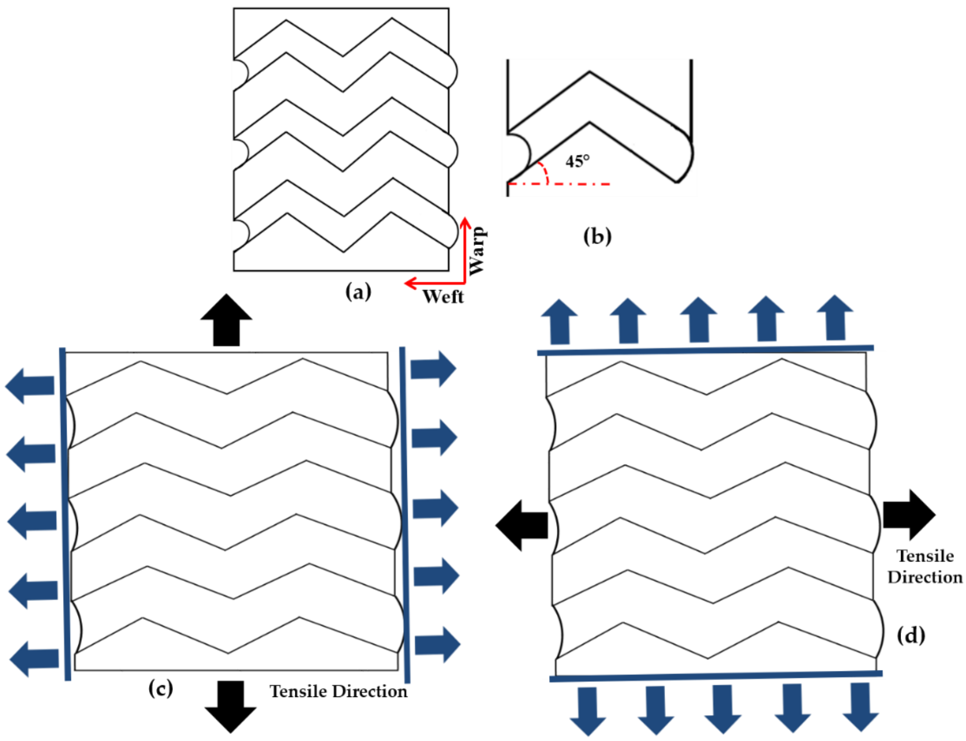


Figure 2. **Double directional folded stripes in parallel in-phase zig-zag fashion: (a) free state; (b) unit cell; (c) stretched state along WD; (c) stretched along FD**

2.2 Transformation of foldable geometry into woven structure

To fabricate bi-stretch auxetic woven fabrics based on the double directional foldable geometry, the conventional elastic and non-elastic yarns were used in both WD and FD together with combination of loose and tight weaves. In the repeating units of the interlacement pattern, the tight weave and loose weaves were arranged alternately in parallel in-phase zig-zag fashion. For the combinations of weaves, Plain weave was used as tight weave, while S4/1, T3/1 and T2/2 weaves with float lengths of 4, 3, and 2 were used as loose weaves. Three combinations were designed with these weaves. The repeating units of the interlacement patterns in terms of number of yarns in WD and FD per unit repeat, for the designed combinations are shown in Figure 3. They are Plain + S4/1 (Figure 3(a)), Plain + T3/1 (Figure 3(b)) and Plain + T2/2 (Figure 3(c)), respectively. In the repeating units, the warp yarns at positions "0" were lowered just to break too long floats in the FD, which were formed by floats of adjacent yarns as shown in the Figure 3(a) and 3(b). It was assumed that upon relaxation, the tight weave area will undergo less shrinkage, whereas the loose weave area will undergo higher shrinkage. Therefore, the differential shrinkage effect will be created within the fabric structural unit cell. The higher shrinkage of loose weave area will force tight weave area to collapse and create double directional folds in parallel in-phase zig-zag fashion which can be unfolded upon stretch to achieve NPR effect. The three loose weaves were used with an intention to study the effect of different float length of loose weave on the creation of folds and the NPR.

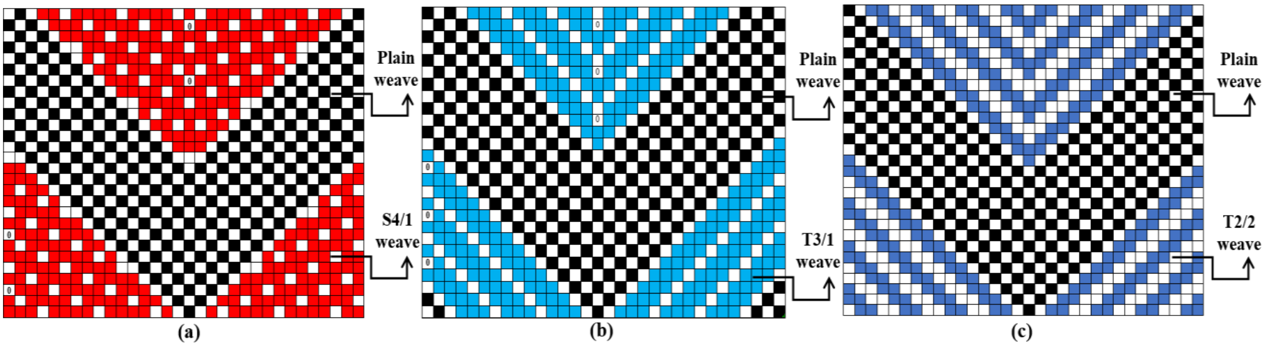


Figure 3. Combinations of loose and tight weaves with parallel in-phase zig-zag double directional foldable geometry running along FD: (a) S4/1 and Plain weave; (b) T3/1 and Plain weave; (c) T2/2 and Plain weave.

Moreover, it was assumed that as the folded lines will run along the FD in a zig-zag fashion upon relaxation, the long floats of weft yarns at loose weave areas also run along the FD. Therefore, if the elastic weft yarns are aligned with the long floats of loose weave in the same direction, there may be more shrinkage and the creation of folds might be enhanced, which will result in more opening of folds and higher NPR effect can be produced. To observe this effect, two variations of fabrics were developed based on two weft yarn arrangements. The first variation was developed by using alternate elastic and non-elastic yarns with a proportion of (50:50) and named as (R, L) arrangement while, the second variation was fabricated by using all elastic yarn with a proportion of (100%) and named as (L) arrangement. The aim of using all elastic weft yarn arrangement was to enhance the folded effect. While for warp yarns, only alternate elastic and non-elastic yarns arrangement with a proportion of (50:50) was used. The fabrics were named by using combination of letter V and F. Letter V was used to indicate the variation number and F to indicate the float lengths. The subscripts of both letters indicate the corresponding numbers. The details of the designed fabrics including yarn arrangements and drawing in draft are given in Table 1.

Table 1. Variations of fabrics developed based on float length of loose weave and weft yarn arrangements

Variation #	1			2		
Fabric ID	V_1F_4	V_1F_3	V_1F_2	V_2F_4	V_2F_3	V_2F_2
Loose Weave	S4/1	T3/1	T2/2	S4/1	T3/1	T2/2
Tight Weave	Plain			Plain		

Weft Yarn Arrangement	(R, L)	(L)
Warp Yarn Arrangement	(R, L)	
Reed denting	(4) warp yarns/ 1 reed dent	
Drawing in draft	(1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,16,15,14,13,12,11,10,9,8,7,6,5,4,3,2)	
R = Non-elastic yarn, L = Core spun cotton spandex elastic yarn		

2.3 Fabrication of auxetic woven fabrics, post weaving treatment and testing of developed fabrics

All the fabrics were fabricated by using Ne 40/1 cotton spun yarn as non-elastic yarn and Ne 40(40D) core spun cotton spandex yarn with a 40denier spandex filament as elastic yarn. The warp density and weft density during weaving process were kept 25.20/cm and 23.62/cm, respectively. The warp yarns were sized before weaving by applying the water soluble Polyvinyl Alcohol (PVA) which can be removed just by washing. As all the fabrics were designed with an idea of using elastic and non-elastic yarns in warp direction, a weaving machine with more than one supplies of weft yarn as well as warp yarns was required to produce these fabrics. The rapier weaving machine manufactured by CCI Intech Taiwan with the options of eight weft supplies, second beam assembly attachment with separate controls and dobby shedding mechanism was used to weave the designed fabrics as listed in Table 1. The speed of weaving machine used was 85RPM. After weaving, the obtained fabrics were first washed for about 45 minutes with Luke warm water (40-45°C), and then dried and allowed to relax at room temperature for 24 hours. After relaxation the thicknesses of the developed fabrics were measured by following standard testing method ASTM D1777-96(2015) and the shrinkage percent in both directions was measured by following equation 1.

$$Shrinkage\% = \left(\frac{Fabric\ dimension\ before\ washing - Fabric\ dimension\ after\ washing}{Fabric\ dimension\ before\ washing}\right) * 100 \quad (1)$$

Since the developed auxetic woven fabrics had extensibility in both directions, tensile tests were carried out along WD and FD until the sample breaks on an Instron 5566 tensile testing machine.

The testing conditions used were load cell (5kN), speed (30mm/min), gauge length (150mm) and jaw size (76.2mm x 25.4mm). The PR was measured at every 1-2% of longitudinal strain. This time of measurement was chosen to observe any change in dimensions even within 1-2% of longitudinal strain. The PR was measured by the method reported by A. Zulifqar et al.,[9]. The photographs of the fabrics obtained by this method were analyzed and the distances of the marks in the photographs were measured along tensile and transverse direction in both free state and stretched state. The engineering strains of the fabric structure in both tensile direction and transversal direction were then calculated based on the measured distances by using Eq. 2 and 3 respectively. The process was repeated for three specimens along WD and FD.

$$\varepsilon_x = \frac{X - X_O}{X_O} \qquad (2)$$

$$\varepsilon_y = \frac{Y - Y_O}{Y_O} \qquad (3)$$

Where ε_x is the longitudinal strain (Ls) and (X_o), (X) are the initial and final length in longitudinal direction respectively, ε_y is the transversal strain (Ts) and (Y_o), (Y) are the initial and final length in transversal direction respectively. Finally, the Poisson's ratio v was calculated using Eq.3 and the PR (v) was calculated using Eq. 4 [1].

$$v = -\frac{\varepsilon_y}{\varepsilon_x} \qquad (4)$$

The results of PR obtained for three specimens along WD and FD at corresponding longitudinal strain were averaged. To confirm the auxetic behavior, the mean values of NPR for three specimens at the corresponding longitudinal strain were used to generate the PR vs. Ls curves. Moreover, to analyze the data and study the effects of float length and weft yarn arrangements, the NPR values, at 2-100% of Ls with interval of 2% were chosen. The effect of float length on NPR in case of (R, L) and (L) weft yarn arrangements separately, was explored by applying two separated, Repeated Measures analyses of variance (ANOVA) tests, followed by paired t-tests with Bonferroni correction. On the other hand, effect of filling yarns arrangements on NPR of three fabrics separately, was explored by applying three separate independent samples t-tests, on the data of three fabrics for both WD and FD. A two-way analyses of variance (ANOVA) with Bonferroni correction was also performed to study any possible interaction between effect of float lengths and weft yarn arrangements on the NPR. All these tests were conducted by using SPSS software [32]. Assuming confidence level of 95%. The p-values less than 0.05 in both performed tests denotes significant difference.

3. Results and discussion

3.1 Realization of folds and NPR effect

Figure 4 shows the thickness and the shrinkage percent in both directions of the developed fabrics after relaxation. It can be observed that for both weft yarn arrangements, the shrinkage percent is higher along FD. In addition, the shrinkage percent along both WD and FD increases with increasing float length. However, by using (L) weft yarn arrangement, the shrinkage percent is increased along FD and decreased along WD for all fabrics. This is because by using (L) weft yarn arrangement, the fabric is more prone to shrink along FD and because of higher shrinkage along FD, the fabric shrinks lesser along WD. Moreover, the thickness of the fabrics is also affected by float length and weft yarn arrangement. It can be observed that the thickness of the fabrics increases with increasing float length for both weft yarn arrangements. However, the thickness of all fabrics decreases by using (L) weft yarn arrangement. This is because with (R, L) weft yarn arrangement, the elastic yarns undergo shrinkage and to facilitate this shrinkage the non-elastic yarn forms loops on the surface of fabric. Therefore, the fabric surface is not smooth which increases the thickness of the fabric. On the other hand, in case of (L) weft yarn arrangement the fabric is more prone to shrink along FD and due to all elastic yarn along weft and lesser shrinkage along WD the fabric surface appeared more smoother and the thickness is reduced.

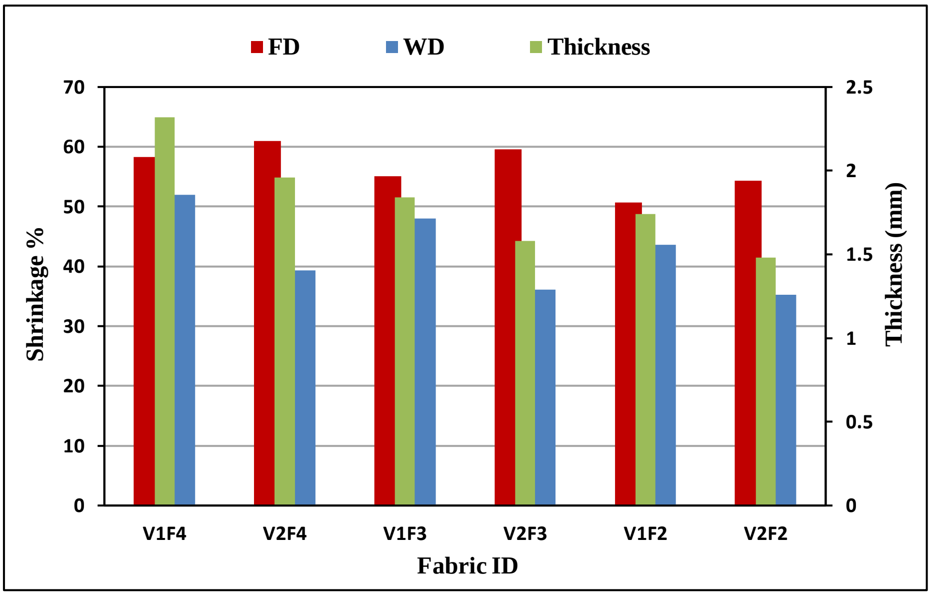


Figure 4. Shrinkage percent and thicknesses of developed fabrics after relaxation

To show the realization of folds, the photographs of a typical fabric V_2F_3 before wash and after wash are shown in Figure 5. The parallel in-phase zig-zag stripes of loose weave and tight weave as designed can be clearly seen in the fabric before wash (Figure 5(a)). It can be observed that after relaxation, the face (Figure 5(b)) and back (Figure 5(c)) of the fabric acquire different appearance due to differential shrinkage effect in both sides of the fabric. At loose weave areas, the warp and weft yarns with long floats are prominent on face and back of the fabric respectively, and the yarns tend to come closer due to more shrinkage of elastic yarns. The fabric at these areas is flat and thicker because of yarn swelling due to shortening of yarn length which is instigated by shrinkage. At tight weave areas with small floats of warp and weft yarns, the yarns are firmly woven and are not as mobile as in loose weave areas. Due to higher shrinkage of elastic yarns at loose weave areas, the yarns at tight weave areas tend to collapse and occupy a bulged or folded form as shown in fabric face (Figure 5(b)) and back of the fabric (Figure 5(c)).

It can also be observed that the folded effect along FD is larger than along WD. This is because the shrinkage percent of fabrics after leaving weaving machine and getting relaxation along FD is higher than that along WD as shown in Figure 4, therefore, larger folded effect is achieved along FD. It is also important to mention that in the relaxed state, the warp yarns and weft yarns do not occupy the same path. Due to more shrinkage at loose weave areas, the warp and weft yarns deviate from the position held by both yarns at the tight weave areas and become closer. Therefore, folds or bulges are created between each two consecutive loose weave areas in the predesigned pattern.

The PR versus Ls curves of the fabric is shown in Figure 6. The NPR effect is produced in both WD and FD directions. Upon stretching along WD or FD, the fabric undergoes tensile deformation and the folded areas open, making it to be expanded in the transverse direction and produce NPR. The curves also show that the NPR effect of the fabric reaches its highest level at low Ls and then reduces with the increase of Ls. Besides, the NPR effect when stretched in WD is higher than that when stretched in FD.

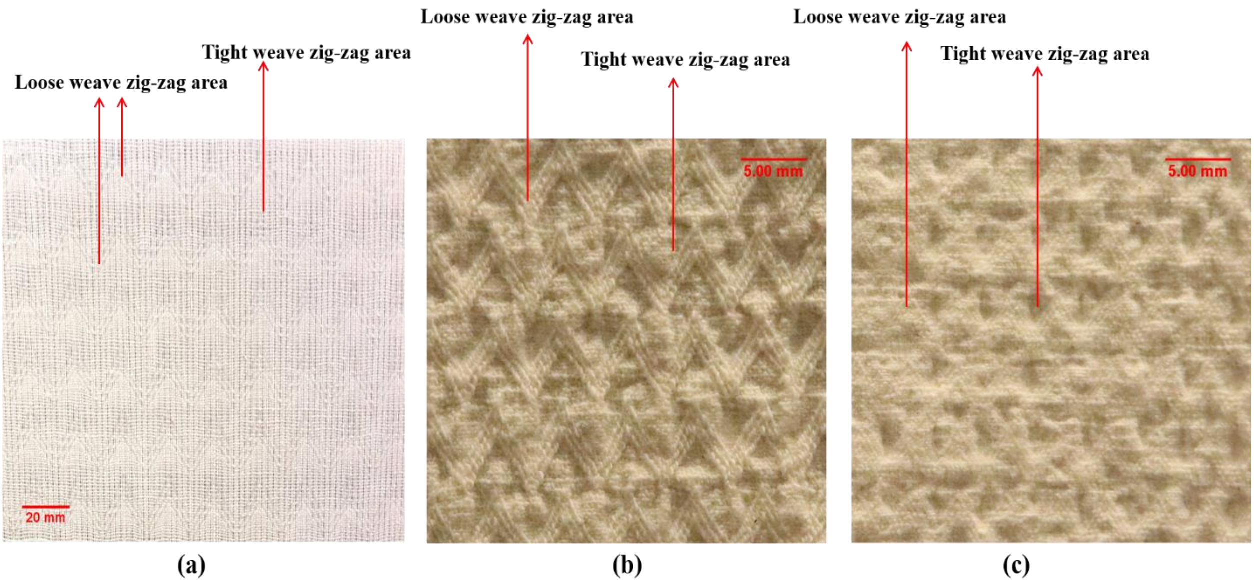


Figure 5. Photographs of a typical auxetic fabric V_2F_3: (a) before relaxation; (b) fabric face after relaxation; (c) fabric back after relaxation.

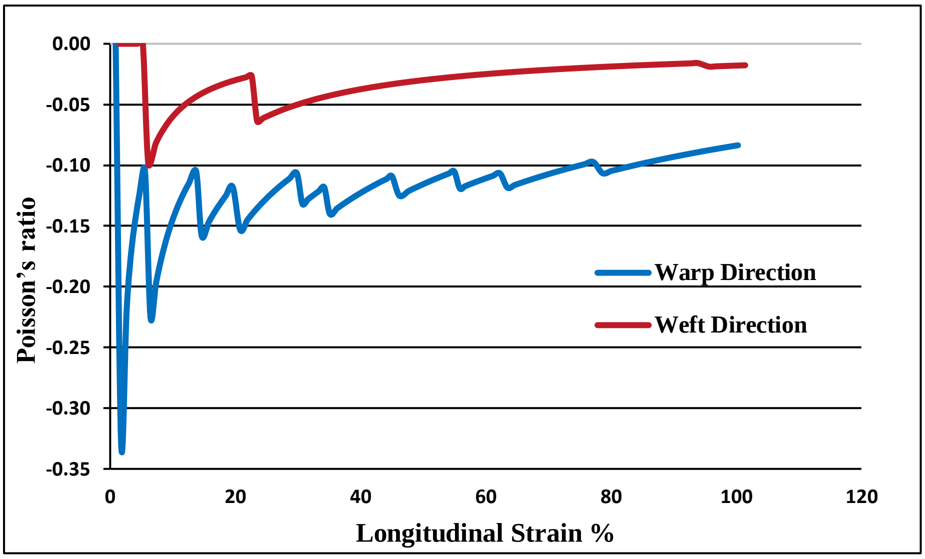
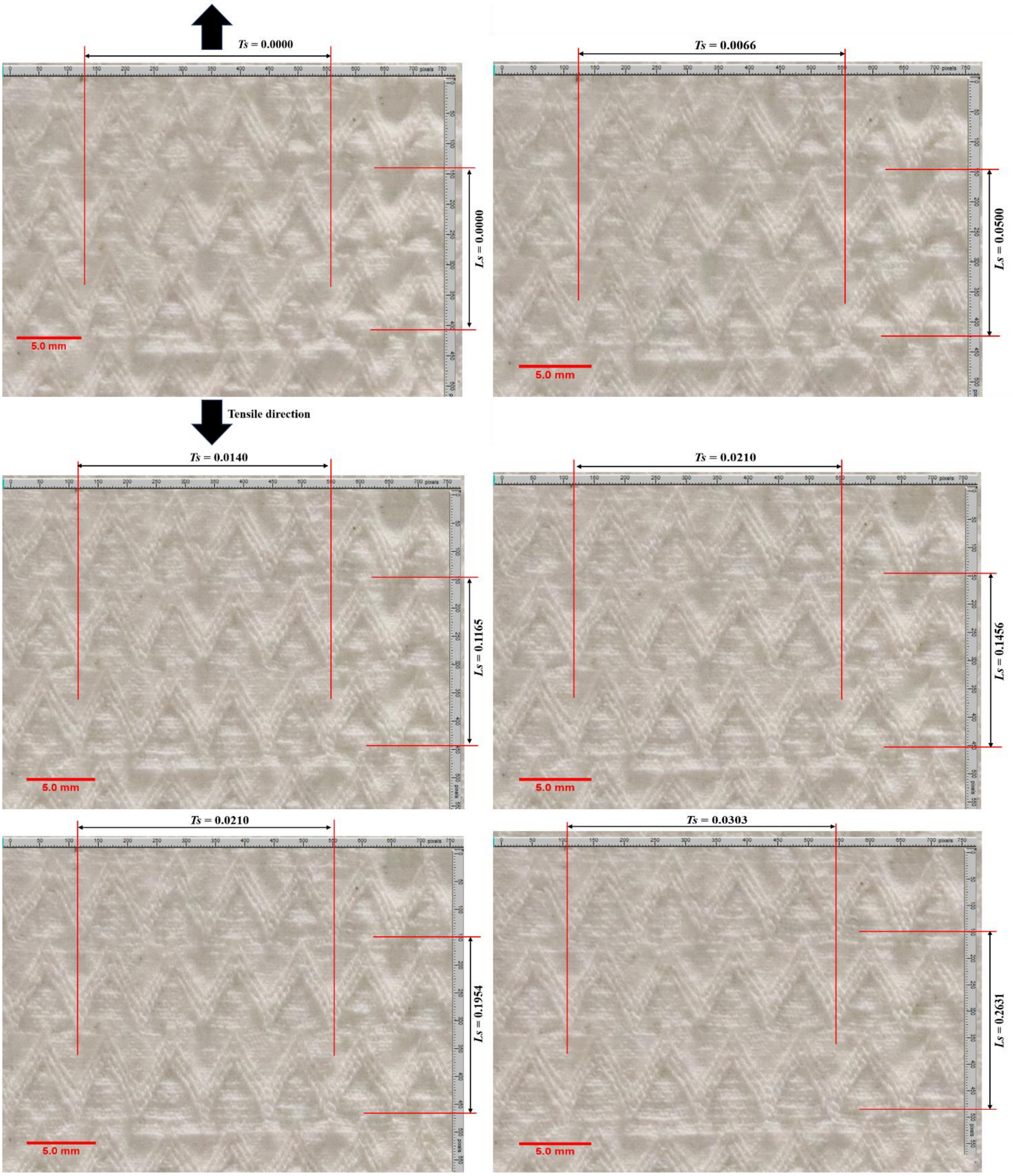


Figure 6. Poisson's ratio vs. longitudinal strain curves of the fabric V_2F_3.

The photos of the fabric taken at different Ls with measured values of Ls and Ts when stretched along WD and FD are shown Figure 7 and Figure 8, respectively. The deformation process of the fabric when stretched in either WD or FD direction can be explained by observing its photos at different Ls and PR vs. Ls curves in Figure 6. When the fabric is stretched in one direction, the transpose of yarn shrinkage at loose weave areas takes place firstly due to more yarns mobility at these areas. The tensile yarns then tend to get straight orientation in tensile direction and an opening of folded areas in the transverse direction also happens immediately at lower Ls. As a result, a higher NPR is produced in the start. After that, the tensile yarns at loose weave areas continue to extend until the transpose of shrinkage at loose weave areas is complete. The tensile yarns then start moving apart to shift towards the position which they held at tight weave areas. This increases the values of Ls, but the transverse dimension remains unchanged. As a result, the NPR effect starts to decrease. When the tensile yarns at loose weave areas are fully extended and shifted to the position which they held at tight weave areas, the sliding of the tensile yarns over the transversal yarns at cross points takes place. This sliding creates frictional forces at cross over points [33], making the transversal yarns to move towards straight orientation. Consequently, the yarns system gets more in order and a more consolidated orientation (straight orientation) is achieved. This straightening of tensile and the transversal yarns continues to open the folded areas in the transverse direction and results in an increase of the fabric width.

This increase is continued with increasing Ls until the maximum opening of folded area is achieved. After the maximum opening is achieved, further increment in transverse dimension is stopped and the tensile force is consumed in increasing the Ls. Therefore, the NPR starts decreasing because of increasing the Ls. This behavior is continued until the frictional forces at the cross over points are overcome and the tensile yarns slip over the transverse yarns (slippage effect).

As mentioned before, the NPR effect of the fabric is higher when stretched along WD than that when stretched along FD. This is because the shrinkage and folded effect is higher along FD. Therefore, when the fabric is stretched along FD, because of higher shrinkage and folded effect along this direction and smaller shrinkage and larger folded effect along WD, the transpose of shrinkage at loose weave areas and the opening of folded area along WD occur at higher Ls which reduce the NPR value. On the other hand, when the fabric is stretched along WD, due to smaller shrinkage and folded effect along this direction and larger folded effect along FD, larger opening of folded area along FD is achieved even at smaller Ls, resulting in higher NPR. This behavior can also be observed from the photos of the fabric taken at different Ls when the fabric is stretched along FD as shown in Figure 8. It can be observed that the folded areas do not open completely even at higher Ls as compared to opening of folded areas when fabric is stretched along WD as shown in Figure 7. In addition, the stick slip effect is observed mainly when the fabric is stretched along WD. This might be because the opening of folded areas and increase in transverse dimensions occurs in steps with increase in Ls. Therefore, the NPR decreases until there is no increase in transverse dimensions due to increase in Ls. The decrease in NPR is sustained up to the Ls value where there is an increase in transverse dimension again, at which the NPR increases again. This behavior is continued until the slippage effect arises.


Ts = 0.0000
Ls = 0.0000
5.0 mm
Tensile direction
Ts = 0.0066
Ls = 0.0500
5.0 mm
Ts = 0.0140
Ls = 0.1165
5.0 mm
Ts = 0.0210
Ls = 0.1456
5.0 mm
Ts = 0.0210
Ls = 0.1954
5.0 mm
Ts = 0.0303
Ls = 0.2631
5.0 mm

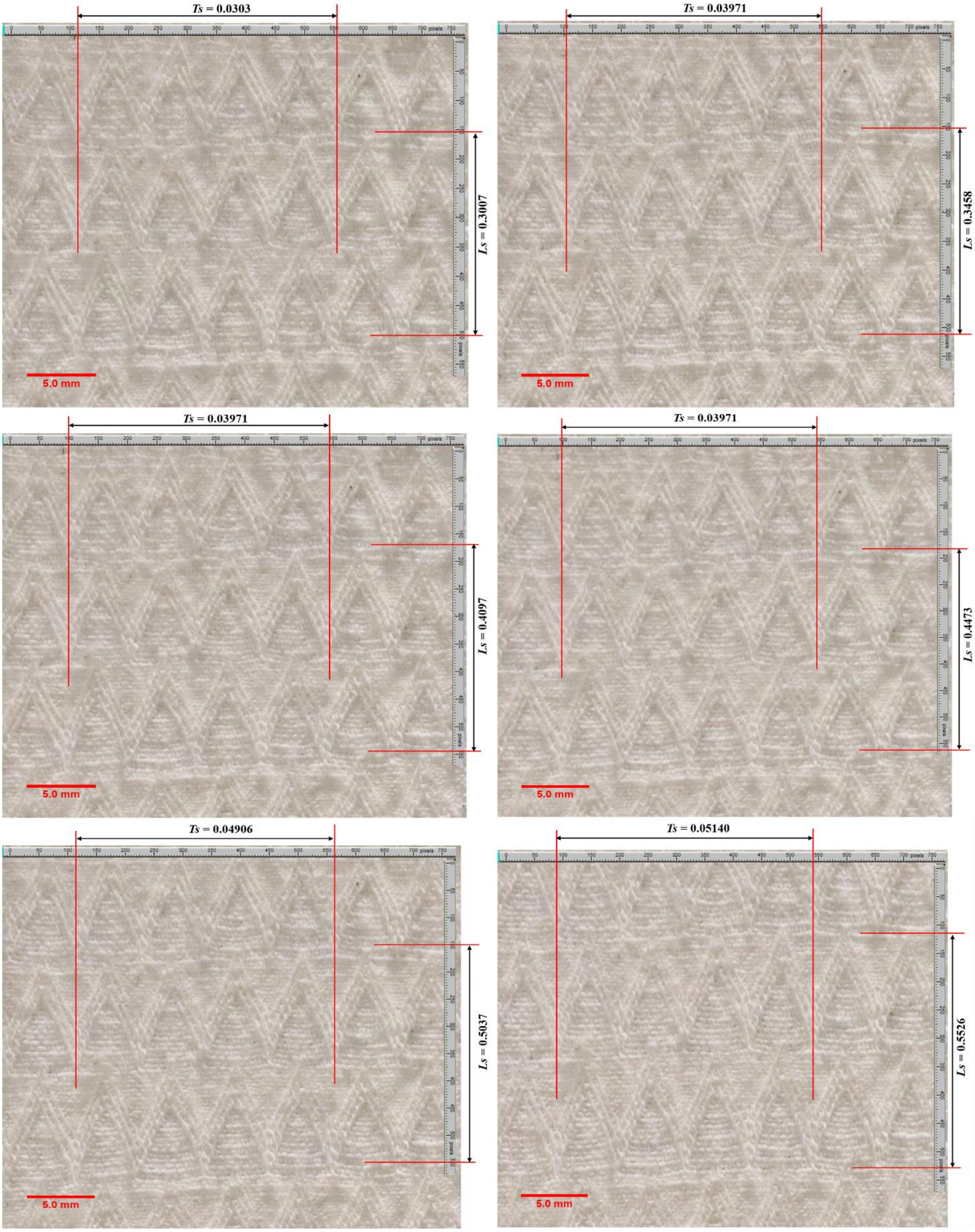
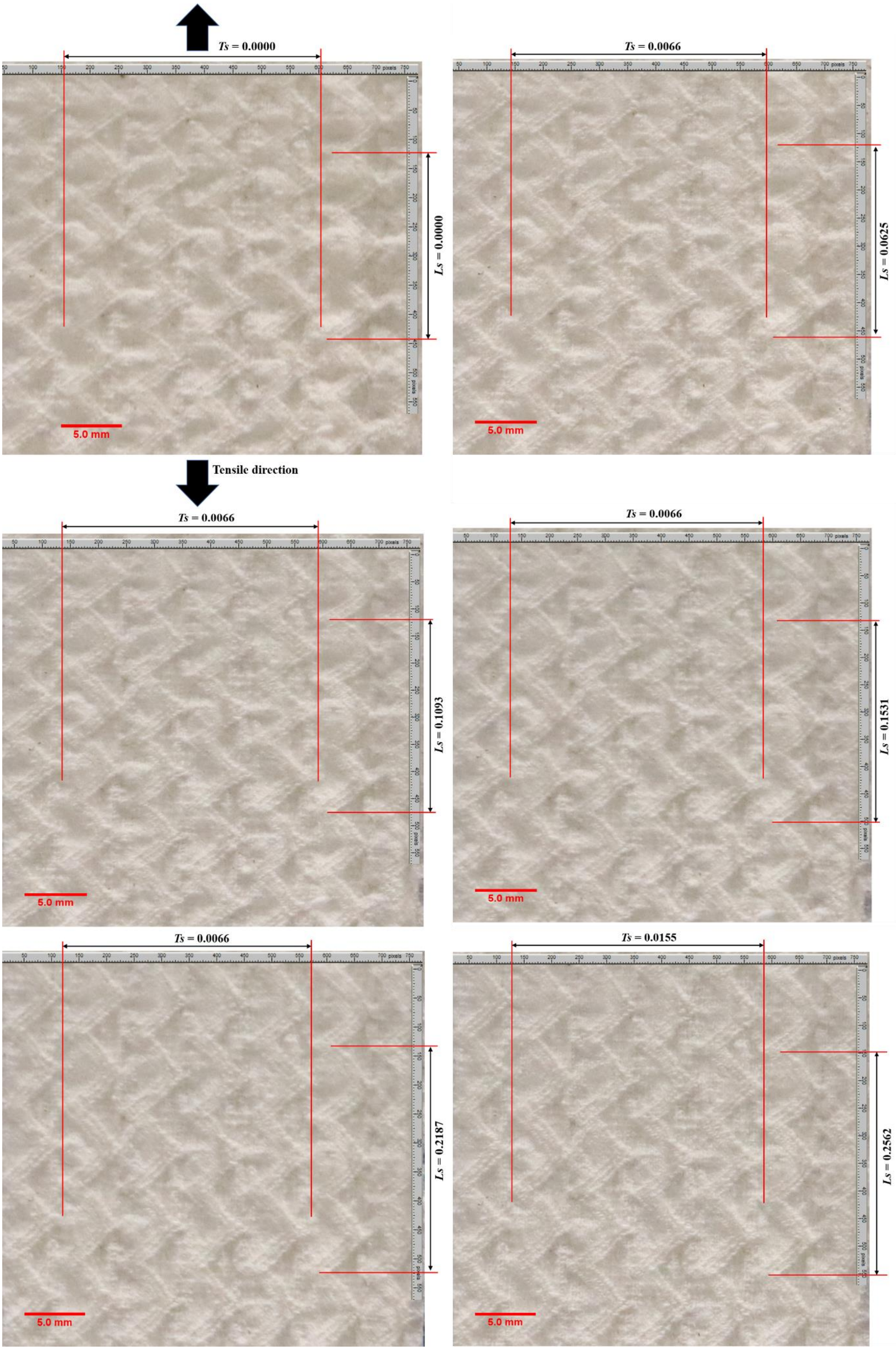


Figure 7. Photos of fabric V_2F_3 taken at different Ls when stretched along WD.



Ts = 0.0000
Ls = 0.0000
5.0 mm
Tensile direction
Ts = 0.0066
Ls = 0.0625
5.0 mm
Ts = 0.0066
Ls = 0.1093
5.0 mm
Ts = 0.0066
Ls = 0.1531
5.0 mm
Ts = 0.0066
Ls = 0.2187
5.0 mm
Ts = 0.0155
Ls = 0.2562
5.0 mm

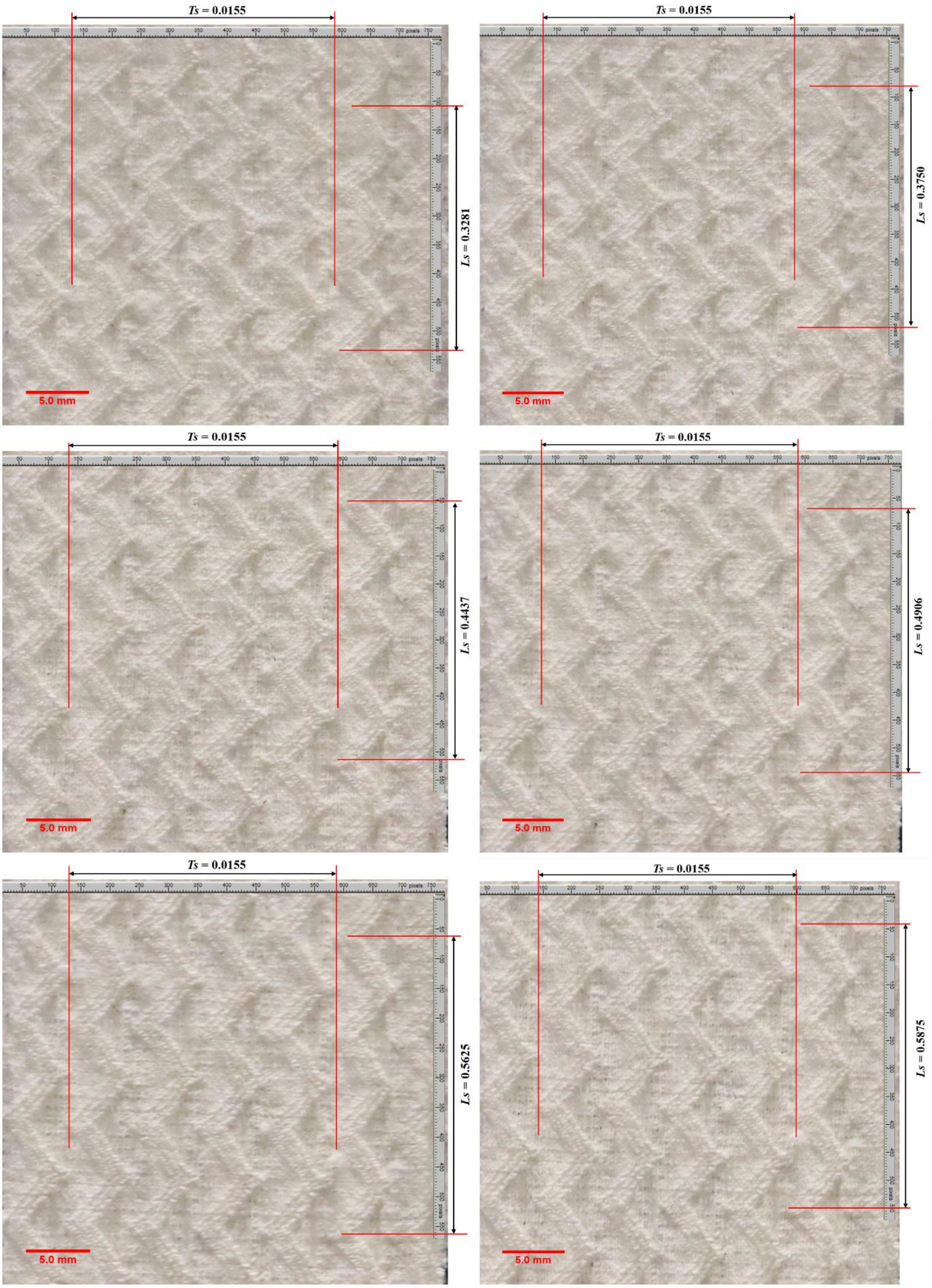


Figure 8. Photos of fabric V_2F_3 taken at different Ls when stretched along FD.

3.2 Effect of float length of loose weave on NPR

From the results of repeated measures (ANOVA), it was found that in case of (R, L) weft yarn arrangement, the float length has a significant effect on the NPR of fabric, when the fabrics were stretched along WD ($p < 0.001$). Post-hoc t-tests indicated that NPR of V_1F_3 was significantly larger than that of V_1F_2 ($p = 0.007$, mean difference = 0.017, 95% CI = 0.004-.030). Furthermore, it was found that NPR of V_1F_3 also significantly larger than V_1F_4 ($p = 0.000$, mean difference = 0.017, 95% CI = 0.011-0.023). On the contrary, there was no significant difference in the NPR of fabrics V_1F_2 and V_1F_4 ($p = 1.000$). In case of fabrics being stretched along FD, repeated measures (ANOVA) results indicated significant effect of float length on the NPR of fabric ($p = 0.02$). Post-hoc paired t-tests indicated that NPR of V_1F_3 was significantly larger than V_1F_4 ($p = 0.017$, mean difference = 0.010, 95% CI = 0.001-0.019) whereas no statistical difference was observed for NPR values of V_1F_2 and V_1F_3, and V_1F_2 and V_1F_4 ($p = 0.121$ and $p = 1.000$ respectively).

In case of (L) weft yarn arrangement, the results of repeated measures (ANOVA) suggested a significant effect of float length on the NPR of fabric, when the fabrics were stretched along WD ($p < 0.001$). Post-hoc t-tests indicated that NPR of V_2F_3 was significantly larger than that of V_2F_2 ($p < 0.001$, mean difference = 0.054, 95% CI = 0.035-0.072) and V_2F_4 ($p = 0.001$, mean difference = 0.029, 95% CI = 0.010-0.047). Furthermore, the difference in the NPR of fabrics V_2F_2 and V_2F_4 was also found significant ($p = 0.003$, mean difference = 0.025, 95% CI = 0.007-0.043). On the other hand, when the fabrics were stretched along FD, repeated measures (ANOVA) results indicate that there was no significant effect of float length on the NPR of fabrics ($p = 0.217$).

To discuss the effect of float length of loose weave on the NPR behavior, PR vs. Ls curves of the fabrics produced with different float lengths (4, 3 and 2) are shown in Figure 9 and Figure 10, respectively for two cases of weft yarn arrangements when stretched along WD (Figure 9(a), Figure 10(a)) and FD (Figure 9(b), Figure 10 (b)). It can be observed that for both the weft yarn arrangements, when stretched along either WD or FD direction, the highest initial NPR and sustained NPR at higher Ls is produced by the fabrics V_1F_3 and V_2F_3, while the lowest initial NPR is produced by the fabric V_1F_2 and V_2F_2 as shown in the (Figure 9(a), Figure 10(a)) and (Figure 9 (b), Figure 10 (b)) respectively. Moreover, the initial NPR effect is produced at higher Ls by the fabric V_1F_2 (Figure 9(a), Figure 9(b)) and V_2F_2 (Figure 10 (a), Figure 10 (b)) than all other fabrics.

In case of the fabrics with (R, L) weft yarn arrangement when stretched along either direction, the lowest sustained NPR at higher Ls is produced by the fabrics V_1F_4 (Figure 9(a), Figure 9(b)). On the other hand, in case of the fabrics with (L) weft yarn arrangement when stretched along WD, the lowest sustained NPR at higher Ls is produced by the fabric V_2F_2 (Figure 10 (a)). When stretched along FD, the sustained NPR of fabric V_2F_4 and V_2F_2 is almost similar and the NPR effect is zero in the start and achieved at higher Ls and then the NPR goes on deceasing with increasing Ls (Figure 10 (b)).

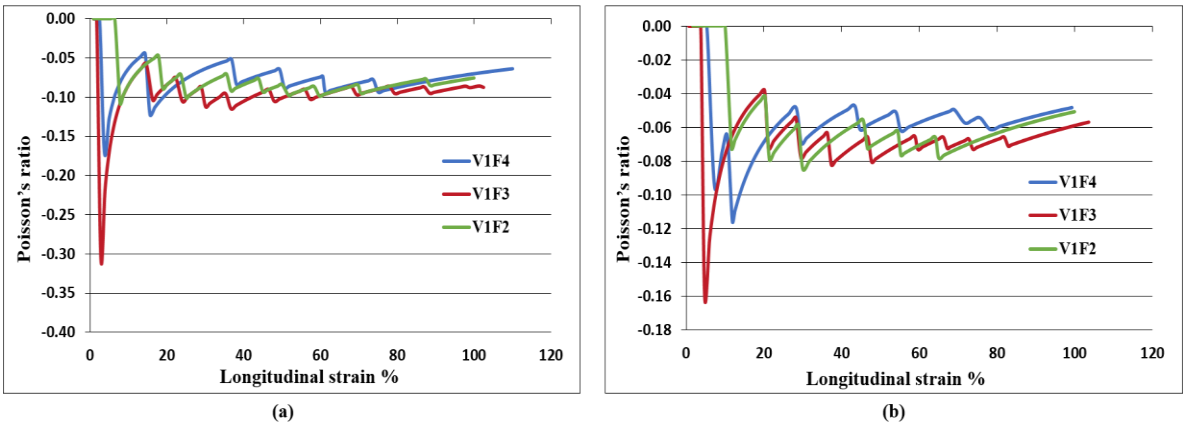


Figure 9. Effect of float length of loose weave on NPR of fabrics with (1R, 1L) weft arrangement: (a) stretched along WD; (b) stretched along FD.

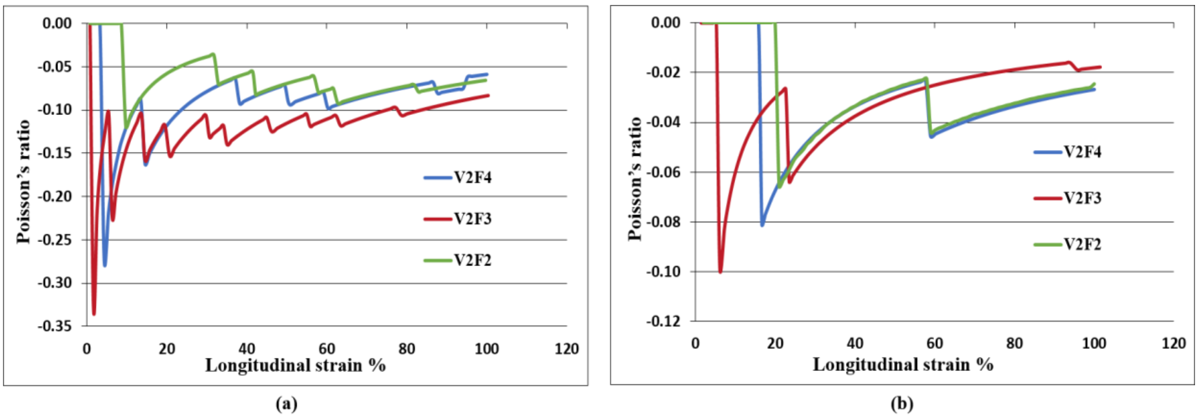


Figure 10. Effect of float length of loose weave on NPR of fabrics with all (L) weft arrangement: (a) stretched along WD; (b) stretched along FD.

However, it is found that the fabrics with the longest float length cannot produce the highest NPR behavior. This phenomenon can be explained by considering the orientation of interlacement points with border lines between loose and tight weaves, as shown in Figure 11. It can be observed that the interlacement points make an orientation of 45°, parallel to border lines between loose and tight weaves, in cases of T3/1 weave (Figure 11(b)) and T2/2 weave (Figure 11 (c)), and another orientation in case of S4/1 weave (Figure 11(a)). Because of this difference in orientation angle, many of warp floats of S4/1 weave may not have completed their full length which are shown as yellow floats in Figure 11 (a). Alike phenomenon happened with weft yarn floats on the other side of fabric. Since the number of shorter than (4) floats are not little in the S4/1 loose weave strip therefore, the shrinkage of such loosely woven strip will be different from a complete S4/1 weave. Besides this, the shrinkage percent in T2/2, T3/1 and S4/1 is in increasing order. However, from T3/1 to S4/1 instead of increasing shrinkage, an unexpected structural folding reform may happen because of altering interlacement pattern. This is also evident from Figure 4, that there is not higher difference in the shrinkages of fabrics with S4/1 and T3/1 weaves. When the fabric is stretched, the opening of irregular folded areas is smaller at smaller Ls and occur at higher Ls resulting in smaller NPR effect. This behavior might be the reason of irregular results for fabric V_1F_4 and V_2F_4.

Conversely, in case of fabric V_1F_3 and V_2F_3, the warp floats of T3/1 weave have completed their full lengths as shown in Figure 11(b). Hence, the shrinkage at loose weave areas is higher and the folded effect is more regular. When the fabric is stretched, the opening of more regular folded areas is larger at smaller Ls and continues to increase with increasing Ls, resulting in higher initial NPR at smaller Ls and higher sustained NPR at higher Ls. On the other hand, in case of fabric V_1F_2 and V_2F_2, due to smaller float length the shrinkage at loose weave areas, the folded effect is smaller. Therefore, when the fabric is stretched, although the transpose of the shrinkage at loose weave areas along the tensile direction is completed earlier, but due to smaller folded effect, the opening of folded area along transverse direction is also smaller, resulting in smaller NPR effect.

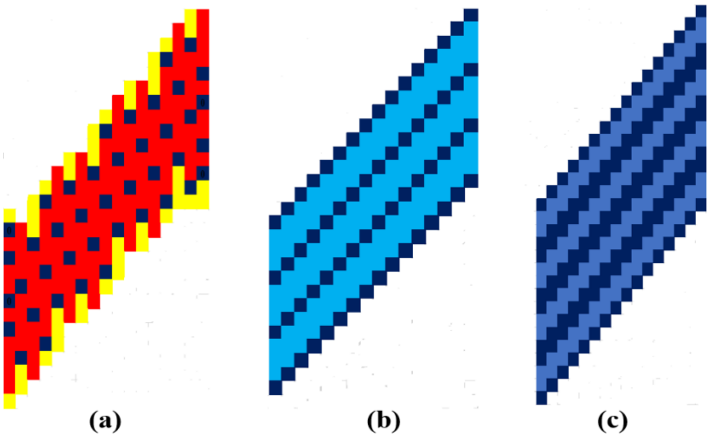


Figure 11. Orientation of interlacement points of loose weaves: (a) S4/1; (b) T3/1; (c) T2/2

3.3 Effect of weft yarn arrangements on NPR

The results of independent-samples t-test including mean, standard deviation, degree of freedom and p-values of NPR are presented in Table 2 for both stretch directions. The results suggested that weft yarn arrangement significantly influences the NPR of fabric. Moreover, the results indicated that when stretched along WD, the NPR of fabrics with float length (3) and (4) was significantly increased by using (L) weft yarn arrangement. Whereas, the NPR of fabric with float length (2) is significantly decreased. However, when stretched along FD the NPR of all fabrics was decreased significantly with (L) weft yarn arrangement.

Table. 2 Results of independent samples t-test (M= mean, SD = standard deviation, df = degree of freedom)

Fabric ID	**WD**				**FD**			
	M	**SD**	**t(df)**	**p-value**	**M**	**SD**	**t(df)**	**p-value**
V_1F_4	-0.0780	0.02204	2.028(98)	0.045	-0.0558	0.01939	-6.529(98)	0.000
V_2F_4	-0.0904	0.03720			-0.0314	0.01796		
V_1F_3	-0.0948	0.02525	3.880(98)	0.000	-0.0658	0.01885	-9.292(98)	0.000
V_2F_3	-0.1190	0.03615			-0.0320	0.01750		
V_1F_2	-0.0780	0.02259	-2.673(98)	0.009	-0.0582	0.02154	-7.794(98)	0.000
V_2F_2	-0.0654	0.02451			-0.0286	0.01604		

Figure 12 to Figure 14 give a comparison of the NPR of the fabrics with (L) and (R, L) weft yarn arrangements. In a general way, the fabrics with (L) weft yarn arrangement have higher NPR effect when stretched along WD, and lower NPR effect when stretched along FD. By considering fabrics with different float lengths of loose weave when stretched in WD, it can be observed that in case of the fabrics with float length (4), although the initial NPR is increased for the fabric with (L) weft yarn arrangement, there is no significant effect on the sustained NPR value at higher Ls for the fabrics with two weft yarn arrangements (Figure 12(a)). In case of the fabrics with float length (3), the initial NPR and sustained NPR at higher Ls are increased by using (L) weft yarn arrangement as shown in Figure 13(a). In case of the fabrics with float length (2), the initial NPR is increased at smaller Ls, but the sustained NPR decreased at higher Ls by using (L) weft yarn arrangement as shown in Figure 14(a). However, **w**hen stretched along FD, the NPR is decreased for all fabrics with (L) weft yarn arrangement as shown in Figure 12(b), 13(b) and 14(b), respectively.

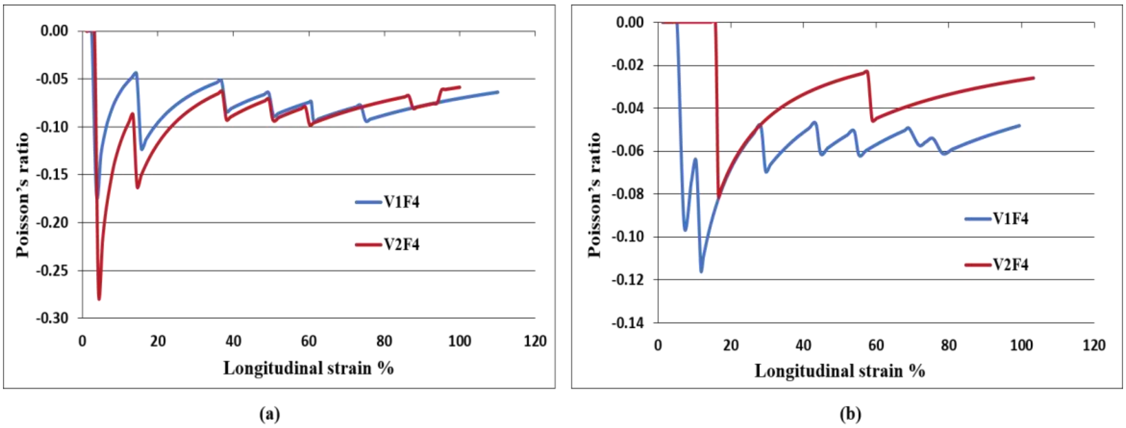


Figure 12. Effect of weft yarn arrangement on NPR for fabrics with float length (4): (a) stretched along WD; (b) stretched along FD.

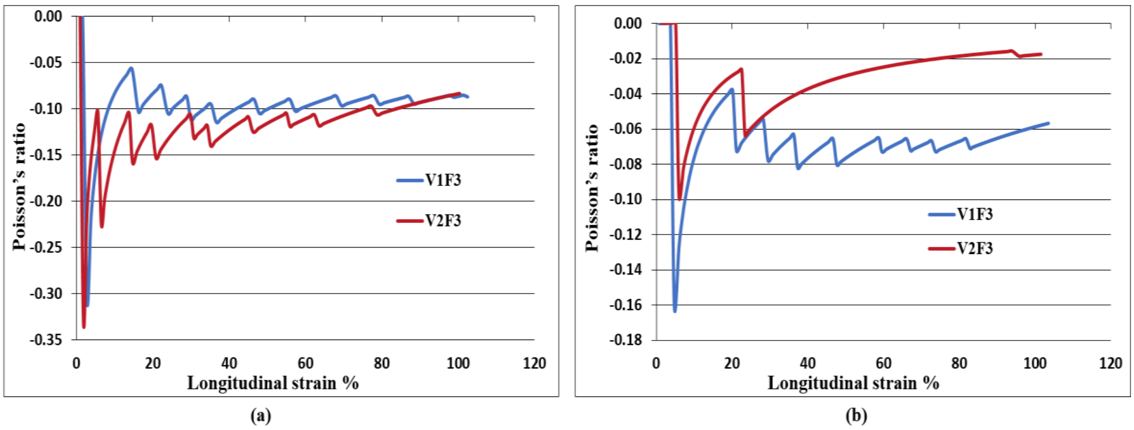


Figure 13. Effect of weft yarn arrangement on NPR for fabrics with float length (3): (a) stretched along WD; (b) stretched along FD.

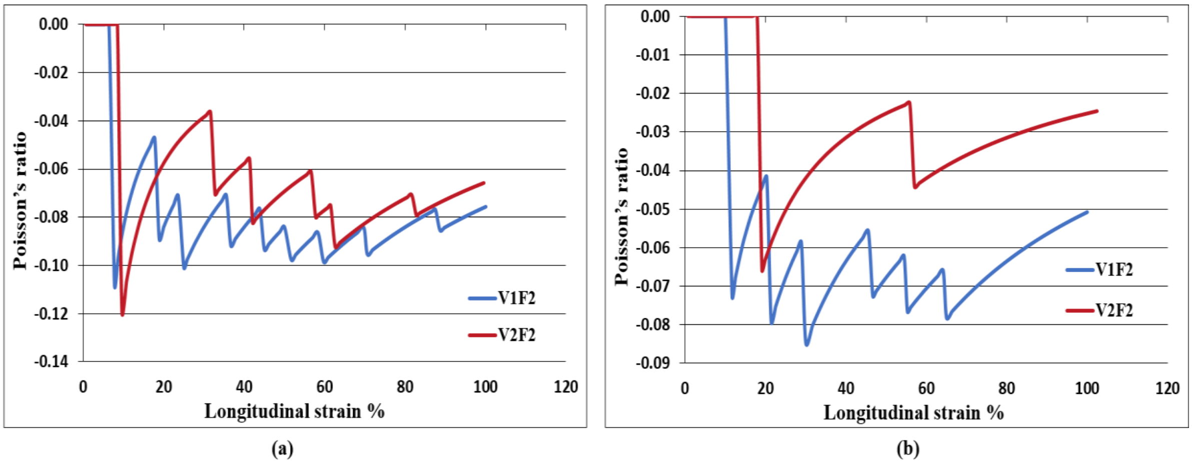


Figure14. Effect of weft yarn arrangement on NPR for fabrics with float length (2): (a) stretched along WD; (b) stretched along FD.

These phenomena can be explained as follows. For the fabrics with float length (4), the higher shrinkage at loose weave areas and irregular folded effect along FD is further enhanced by using (L) weft yarn arrangement. When the fabric is stretched along WD due to enhanced folded effect, the opening of folded areas is also achieved at smaller Ls, resulting in higher NPR at smaller Ls. However, further opening is restricted by the higher shrinkage at loose weave areas at higher Ls, resulting in a decreasing of the NPR at higher Ls. For the fabric with float length (3), the regular folded effect along FD is further enhanced by using only elastic yarns in FD. Therefore, upon stretching along WD, larger opening of folded areas is achieved even at smaller Ls and further increases with increase of Ls, resulting in higher initial NPR and sustained NPR at higher Ls. For the fabrics with float length (2), the folded effect in the fabric is reduced due to smaller differential shrinkage effect between the tight weave and loose weave. The use of all (L) arrangement in FD further reduces this differential shrinkage effect of two weaves. Therefore, when the fabric is stretched, the opening of folded areas occurs and completes at smaller Ls and there is no further opening at higher Ls. Consequently, the NPR is increased initially and then decreases with increasing Ls. In case when stretched along FD, as the folded effect of fabrics is further increased by using all elastic yarns in weft direction, the value of Ls will increase. As a result, the NPR is reduced for the fabrics with all elastic yarns. Furthermore, the results of two-way ANOVA test are presented in Table 3 while the interaction plots are presented in Figure 15. The results indicated that when the fabrics are stretched along

WD, the NPR of fabric is significantly influenced by float length ($p < 0.001$) and weft yarn arrangement ($p = 0.016$). On the other hand, when the fabrics are stretched along FD, weft yarn arrangement significantly affects the NPR of fabric ($p < 0.001$), but the effect of float length is not significant ($p = 0.062$). Furthermore, the results of two-way ANOVA indicated that the effect of float length on the NPR of fabric significantly depends on weft yarn arrangement when the fabric is stretched along WD. The ($p < 0.001$) value confirms that there is a significant interaction between two factors as shown in Figure 15(a). However, when the fabric is stretched along FD there is no significant interaction found between effect of float length and weft yarn arrangement ($p = 0.204$) as shown in Figure 15(b).

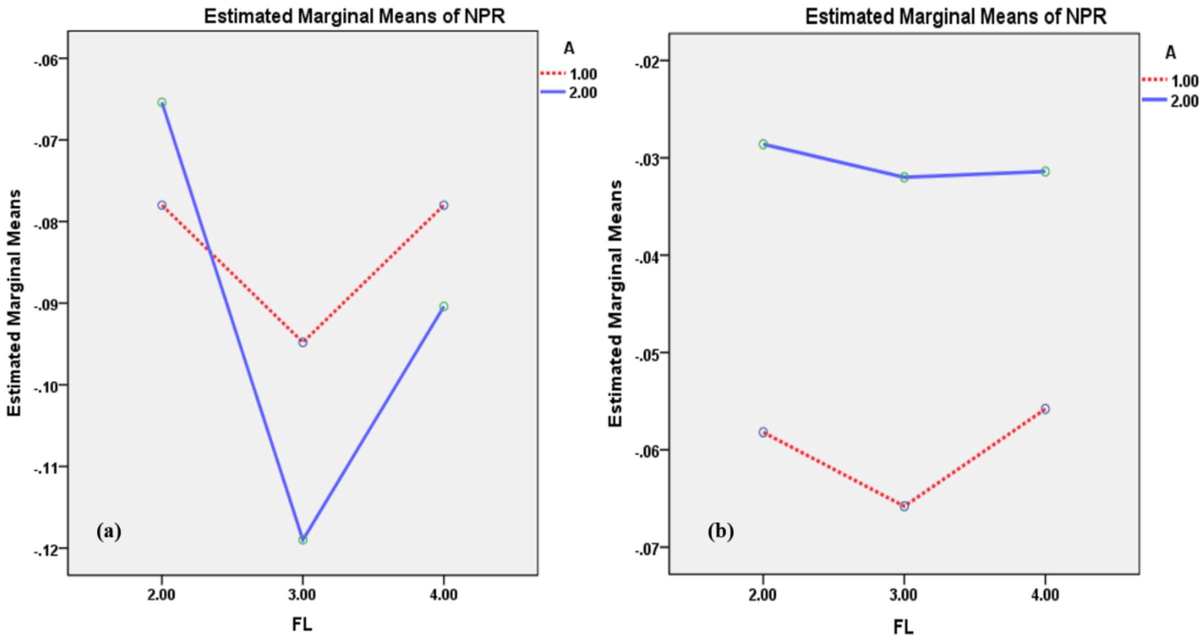


Figure 15. Interaction plots of effect float length on NPR and weft yarn arrangement (2): (a) stretched along WD; (b) stretched along FD.

Table 3. **Effect of weft arrangement and float length on the NPR: (a) stretched along WD; (b) stretched along FD**

Variables	Sum of Squares	df	Mean Square	F	p-value	Partial Eta Squared
(a)						
Weft Arrangement (A)	.005	1	.005	5.848	.016	.020
Float Length (FL)	.064	2	.032	38.792	.000	.209
A * FL	.018	2	.009	10.753	.0000311	.068
Error	.241	294	.001			
Total	2.630	300				
Corrected Total	.327	299				
R Squared = .263 (Adjusted R Squared = .251), Dependent Variable: NPR						
(b)						
Weft arrangement (A)	.064	1	.064	185.203	.000	.386
FL	.002	2	.001	2.805	.062	.019
A * FL	.001	2	.001	1.598	.204	.011
Error	.102	294	.000			
Total	.785	300				
Corrected Total	.169	299				
R Squared = .398 (Adjusted R Squared = .387), Dependent Variable: NPR						

4. Conclusions

This study reports the development of a novel class of bi-stretch auxetic woven fabrics by using conventional elastic and non-elastic yarns and available weaving machinery. The phenomenon of differential shrinkage is created to realize parallel in-phase zig-zag double directional foldable geometry running along FD into woven architecture. The developed fabrics exhibited NPR effect over a larger strain range when stretched along WD or FD. From this study, the following conclusions can be drawn.

1. The parallel in-phase zig-zag double directional foldable geometry can be realized into bi-stretch auxetic woven fabrics by creating differential shrinkage phenomenon within the fabric structural unit cell due to combinations of loose and tight weaves and the use of non-auxetic elastic and non-elastic yarns along both WD and FD.
2. The creation of folded effect depends upon the number of completed yarn floats within the loose weave area. Higher the number of completed yarn floats within the loose weave area, more regular will be the folded effect.

3. The shrinkage in WD and FD directions is different. Higher shrinkage is obtained in FD.
4. By using (L) weft yarn arrangement, the shrinkage in FD is increased but the shrinkage in WD is decreased.
5. The NPR effect in WD and FD directions is different. Higher NPR effect is obtained when stretched along WD.
6. The float length of loose weave has significant effect on NPR behavior of fabrics. However, the higher float length does not mean that it will produce higher NPR. The highest NPR effect is produced by the fabric with float length of (3).
7. The weft yarn arrangement also has significant effect on NPR. The (L) weft yarn arrangement can increase the NPR effect when stretched along WD but reduce the NPR effect when stretched along FD.
8. The effect of float length on the NPR of fabric significantly depends on weft yarn arrangement when the fabric is stretched along WD.

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