Deformation Behavior of Auxetic Woven Fabric Based on Re-entrant Hexagonal Geometry in Different Tensile Directions

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Abstract

Auxetic woven fabrics made of non-auxetic yarns have gained interest of textile scientists in recent times. Such fabrics have already been produced and investigated for their negative Poisson's ratio (NPR) effect in two principle directions. However, the NPR effect of these fabrics in different biased tensile directions has not been studied. Especially, the influence of repeated tensile loading on the NPR effect retention ability of fabric has not been explored yet. Therefore, this paper aims to report the NPR effect of auxetic woven fabric in different tensile directions and the influence of repeating tensile cycle tests on its NPR effect retention ability. The auxetic woven fabric is firstly fabricated based on a re-entrant hexagonal geometrical structure by using elastic and non-elastic yarns, and then subjected to single and repeating tensile tests in five different tensile directions, which include two principle directions and three biased directions. It is found that the NPR effect is largely dependent upon the tensile direction and the number of repeating tensile cycles.

Keywords: negative Poisson's ratio, repeating tensile test, auxetic woven fabric, re-entrant geometry

1. Introduction

Auxetic textile materials have negative Poison's ratio (NPR) that makes them to expand or shrink laterally when they are stretched or compressed, respectively [1-4]. The word auxetic came from the Greek word (αὐξητικός (auxetikos)) that means "something which tends to increase"[5]. Auxetic textile materials that have been developed and investigated up till today include auxetic yarns [6-12], auxetic woven fabrics [10, 11, 13-17], auxetic weft knitted fabrics [18-23], auxetic warp knitted fabrics [24, 25], 3D auxetic textile reinforcements [26], auxetic braided structures [27, 28], auxetic non-woven [29] and auxetic textile composites [9]. Among them, auxetic fabrics have gained the attention of the textile researchers in recent years because of their exceptional properties. These include enhanced porosity under tensile stress [30] and synclastic behavior under bending condition which results in better formability and improves the shape fitting at the joint parts of the human body [31]. These counterintuitive properties make auxetic fabrics a potential candidate for many applications such as sportswear [32], maternity wear [3], children's wear [24], and medical applications [33, 34].

Until today, two methods have been implemented to produce auxetic fabrics. The first method is to use auxetic yarns and weaving technology to produce auxetic fabrics. Using this method, a two-ply plain woven narrow fabric made of helical auxetic yarn in warp was produced with an in-plane NPR of -0.1 at a tensile strain of 32% [10]. Likewise, Miller et al. reported an auxetic woven fabric made of helical auxetic yarns. A plain-woven fabric was also produced with a double helix auxetic yarn in weft and a meta-aramid fibre in warp. This fabric produced an NPR of -0.1 when stretched between two glass plates at constant separation [9]. In another study, Wing and Hu developed auxetic woven fabrics using auxetic plied yarns[35]. However, the production of auxetic fabrics using auxetic yarns is not widely used because the availability of the auxetic yarns is inadequate in the current market. In addition, the NPR effect of auxetic yarns cannot be transferred completely to woven fabrics, because of the obstructions rendered by the interlacement points in the woven fabric structure.

The second method is to fabricate auxetic fabrics based on the realization of auxetic geometry into the fabric structure by using non-auxetic yarns. This method has attracted many researchers because there is no limitation for fiber materials and fabric structures. Employing this method, Liu, Hu et al. developed a series of auxetic knitted fabrics based on different geometrical structures such as re-entrant hexagons, rotating units, and folded structures [19]. It was also reported that auxetic fabrics could be fabricated by using warp knitting technology [24, 25]. However, the real applications of developed auxetic knitted fabrics are still limited, due to low structural stability, low elastic recovery and higher thickness. The developments of uni and bi-stretch auxetic woven fabrics by using non-auxetic elastic and non-elastic yarns have also been reported recently [14-17]. Adeel et al. found that the bi-stretch fabrics based on re-entrant hexagonal geometrical structure (REHG) could produce an NPR of -0.35 when stretched in warp direction [14, 17]. In another study, Cao et al. reported that the bi-stretch auxetic woven fabrics based on the foldable geometry could produce an NPR up to -0.36 and -0.27 when stretched in warp and weft direction, respectively [15].

The main attainment of these developments is to use conventional non-auxetic yarns and weaving machinery to fabricate auxetic woven fabrics, which did not exist earlier. In addition, the developed auxetic woven fabrics showed larger NPR effect over a wide range of tensile strain. These fabrics filled the gap and provided a foundation for the advancement of research in the area of auxetic woven fabrics made of non-auxetic yarns. However, there are certain shortcomings associated with these fabrics. Firstly, the NPR effect in different tensile direction of the auxetic woven fabrics is still unaddressed. Secondly, the retention ability of NPR effect under repeating tensile cycles (RTC) has not been explored yet. To address these shortcomings, it is essential to study the NPR effect in different tensile directions, because the fabrics are not only stretched in the warp or weft directions but also undergo stretch in other tensile directions during real life usage. Therefore, such a study can provide more consolidated information about the NPR effect of the auxetic woven fabrics in different tensile directions. In addition, the developed auxetic woven fabrics are suggested for tight garments, which are required to undergo repeated tensile loading during real usage. Therefore, it is also of vital importance to study its NPR effect under repeated tensile loading condition.

This paper reports an extended study on the NPR effect of the auxetic woven fabric based on REHG. To address the above-mentioned shortcomings of the previously developed auxetic woven fabric, the tensile tests were conducted to study the NPR effect in five different tensile directions including two principle and three biased directions. In addition, the fabric was stretched repeatedly up to 25% of tensile strain to study its retention ability of the NPR effect under RTC.

2. Methodology

2.1. Preparation of fabric specimens

Auxetic woven fabric used was fabricated based on REHG by inducing NPR effect into the fabric structure. The previous study has shown that an approximation of REHG could be realized into woven fabric by creating differential shrinkage effect or the phenomenon of non-uniform contraction profile within the unit cell of woven fabric structure[14, 17]. This effect could be created using elastic and non-elastic yarns by combination of loose and tight weaves with different contraction properties. Figure 1(a) schematically shows the arrangement of different weaves within the unit cell of the interlacement pattern of the fabric. There are three sections, namely section A, section B, and section C, with weaves having different tightness and shrinkage properties as shown in Figure 1(b-d), respectively. Section A is based on a loose satin weave (4/1), section B has a tight plain weave (1/1) and section C is made by an extremely loose weave where each alternate warp yarn is raised above the weft yarn. Therefore, the order of weaving tightness of the weaves at these three sections is B>A>C. Based on this interlacement pattern, auxetic woven fabric was fabricated by using a 14.8 Tex core spun cotton spandex elastic yarn and 14.8 Tex cotton spun non-elastic yarn. A 4.44 Tex spandex filament was used as the core of the elastic yarn. While alternate elastic and non-elastic yarns were used in the warp direction, only elastic yarn was used in the weft direction. The weft and warp densities used were of 31.50/cm and 25.20/cm, respectively. A rapier weaving machine (Model: SL8900S) manufactured by CCI Intech Taiwan was used for weaving the fabric. After weaving, the fabric was subjected to relax for 48 hours at a maintained standard temperature (25±2^{0}C) and atmosphere (65±5^0); then the fabric was washed for 45 minutes by using a Whirlpool washing machine (Model: 3LWTW4840YW) with lukewarm water (40–45^{0}C) followed by drying and relaxation at room temperature for 24 hours. The objective of washing was to remove water soluble sizing chemical (PVA: Poly Vinyl Alcohol) which was used for the sizing of warp yarn. At the relaxed state of the fabric, different shrinkage effect was created at different sections and the order of shrinkage of the three sections was C>A>B. Since section B is placed between section C and section A, therefore because of the shrinkage difference of these two sections, the edges of section B are crumpled diagonally, thus creating an approximation of the REHG unit cell.

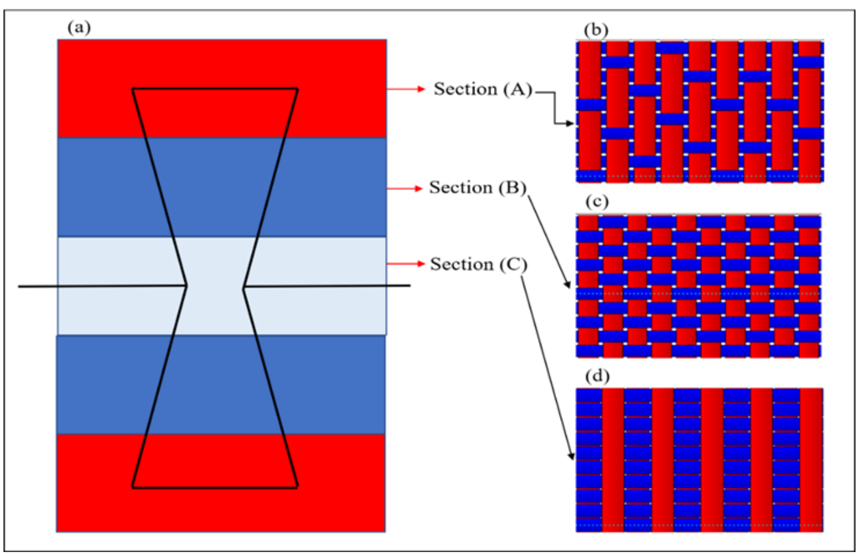

Figure 1. Realization of the REHG structure into the woven fabric: (a) schematic illustration of arrangement of different weaves within the unit cell of the interlacement pattern; (b) weave in section A; (c) weave in section B; (d) weave in section C.

Figure 2(a) shows the auxetic woven fabric fabricated. The unit cell of the fabric structure is outlined, and it can be seen that the segments (a-b) and (c-d) make the horizontal ribs, and the segments (a-f), (f-c), (b-e) and (e-d) make the diagonal ribs thus realizing an approximation of a unit cell of the REHG structure. The angle between the horizontal rib and the diagonal rib is indicated by β as shown in Figure 2(a), where ∠baf = β, and ∠bed = 2β. When the structure of the fabric is stretched in either direction, the diagonal rib segments will rotate to the warp direction, leading to an increase in the distance between points e and f. As a result, the dimensions of the whole structure increase and an NPR effect is achieved.

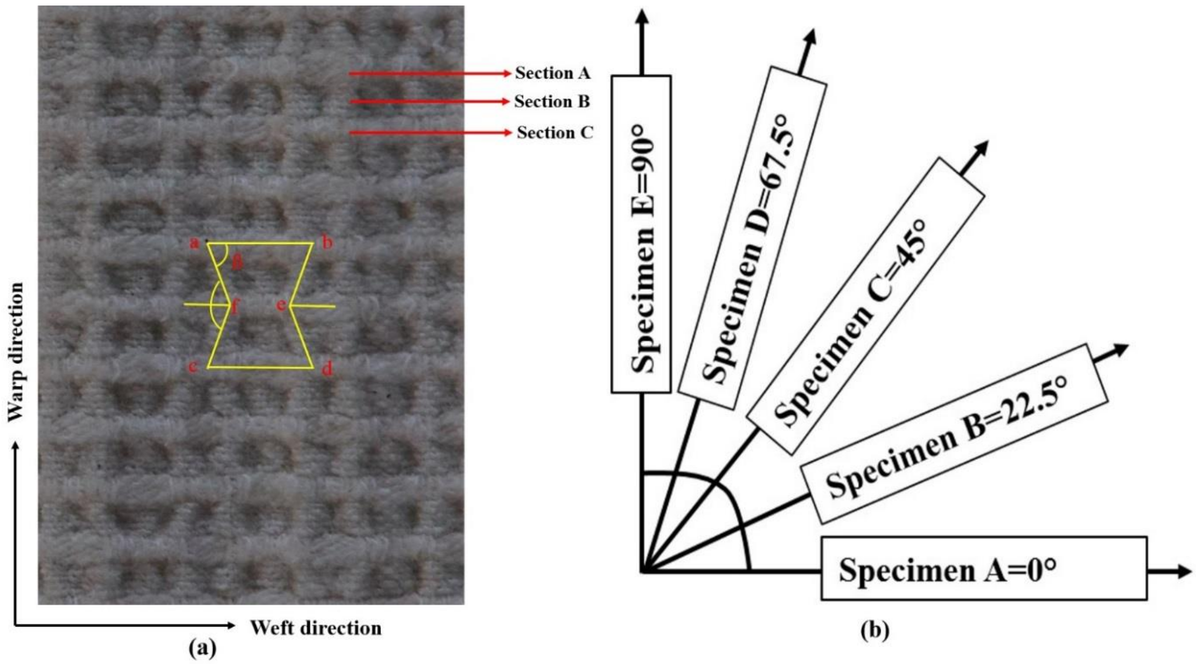

Figure 2. Preparation of fabric specimens: (a) relaxed auxetic woven fabric showing different sections and outline of the fabric structural unit cell; (b) schematic of specimen preparation showing different tensile directions.

Figure 2(b) shows the schematic illustrations of testing specimens prepared for tensile tests. The specimens in five different tensile direction were prepared. Among those, two specimens including specimen A and E were prepared along the principal directions (weft and warp directions respectively), and three specimens were prepared along biased directions (other than principal directions). To prepare the specimens along biased directions, the weft direction was considered as the reference direction. Therefore, the specimen A and E along weft and warp directions were considered as specimens along 0º and 90º directions. The specimens along three biased directions include specimen B, C, and D along directions at angles of 22.5º, 45º and 67.5º relative to weft direction. Figure 3 shows the photos of specimens prepared for each tensile direction.

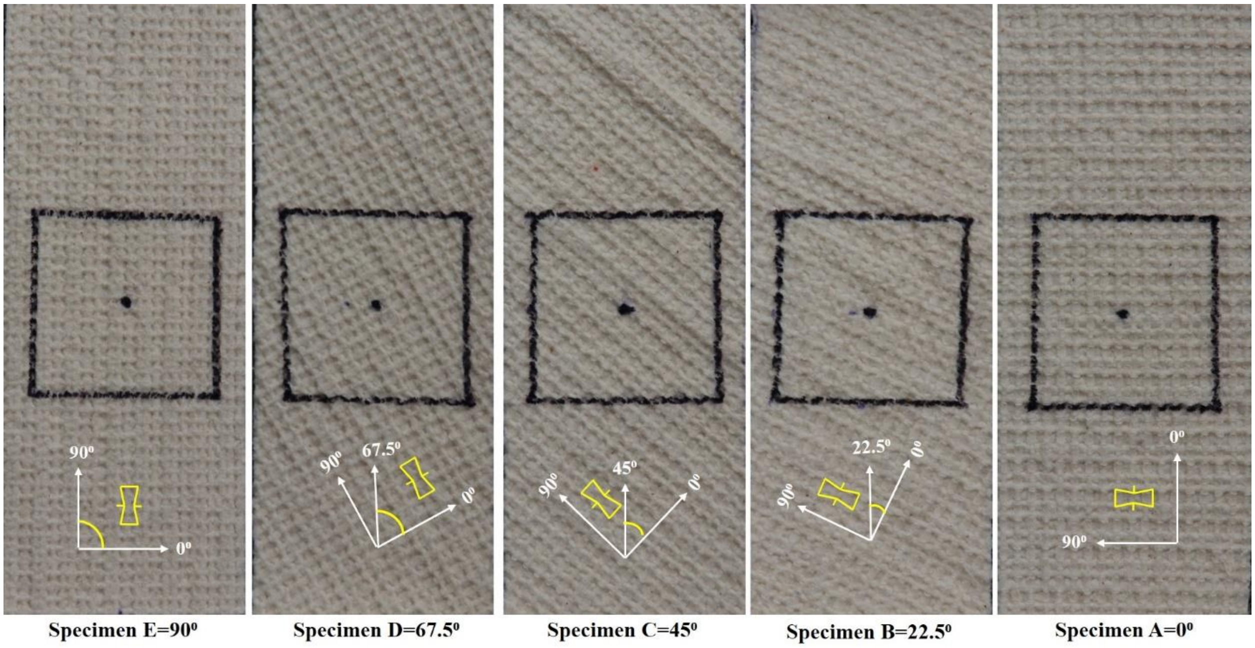

Figure 3. Photos of the prepared testing specimens in different tensile directions.

2.2. Tensile tests

Tensile tests were conducted on an Instron 5566 tensile testing machine (Instron Ltd., High Wycombe, England). Figure 4(a) and (b) shows the testing specimen and the photo of the testing setup respectively. The selected testing parameters included the gauge length (150 mm), crosshead speed (50 mm/min), pre-tension (0.2N) and the sample size(200 mm × 50 mm). Three replicates were tested in each tensile direction with the same tensile directions. While the tensile stress-strain curves were automaticlly generated from the tensile machine, the Poisson's ratio needed an additional device to measure the deformation of the specimen in both the tensile and transversal directions. Therefore, a square was marked on the specimen to facilitate the measurement of the size changes in these two directions during the tensile tests, as shown in Figure 4(a). At the same time, a high-resolution camera (Canon-EOS 80D, Tokyo, Japan) was placed on a tripod in front of the tensile testing machine to video record the tensile testing process, as shown in Figure 4(b). The photos were then extracted from the video after every 2-3 seconds or every 1% of tensile strain. A photo was also taken before the start of tensile testing which was considered as the photo of the specimen at the un-stretched state. This photo was used to make a comparison with photos of fabric extracted from the video at different tensile strains. In the photos, the distances between the line marks in tensile and transverse directions were measured via a screen ruler for both stretched and un-stretched states of each specimen. After that, the engineering strains of the fabric structure was calculated in both the transversal and tensile directions through equations (1) and (2). The Poisson's ration v was then calculated via equation (3).

$$\varepsilon_y = \frac{Y - Y_0}{Y_0} \tag{1}$$

$$\varepsilon_x = \frac{X - X_0}{X_0} \tag{2}$$

$$v = -\frac{\varepsilon_y}{\varepsilon_x} \tag{3}$$

Where ε_y is the transversal strain, Y and Y_0 are the initial and extended length in the transversal direction, respectively, ε_x is the tensile strain, X and X_0 are the initial and extended length in the tensile direction, respectively.

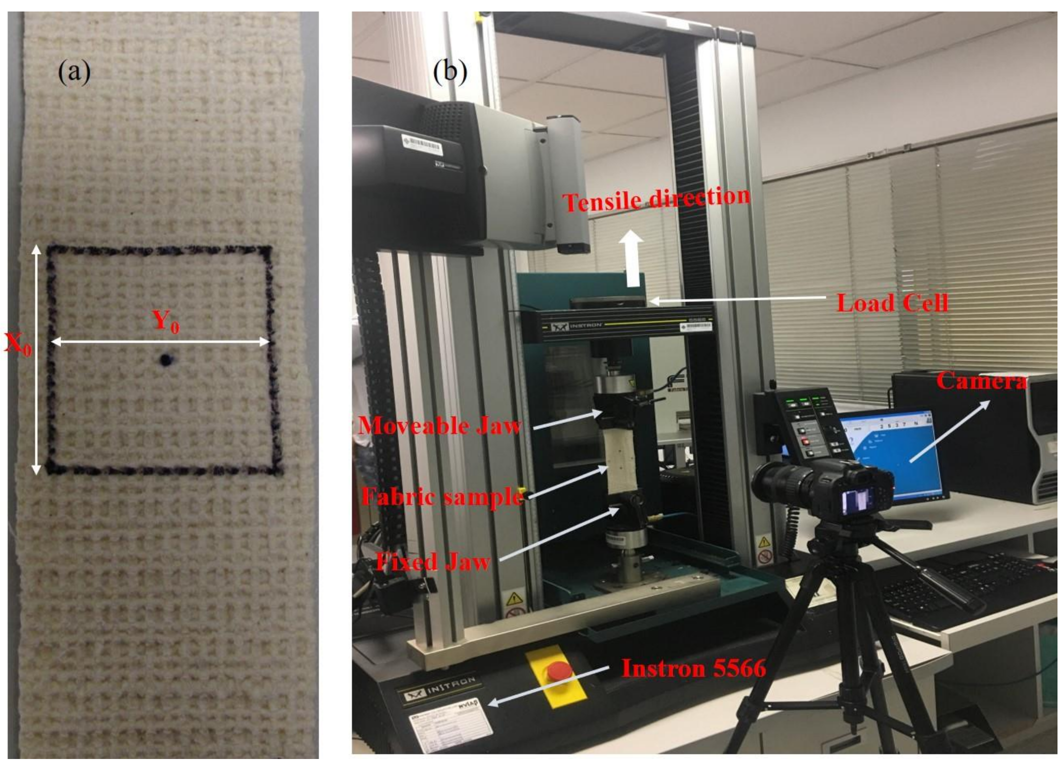

Figure 4. Tensile testing of the auxetic woven fabric: (a) fabric specimen; (b) photo of the tensile testing setup.

The RTC test was also carried out in each tensile direction using the same testing setup and parameters for 20 cycles. The process for the RTC test is schematically shown in Figure 5 and total 102 seconds are required to complete one tensile cycle. During each tensile cycle, the fabric specimen was stretched up to 25% of the tensile strain in the first 45 seconds, then it was kept there for 2 seconds, after that, it was returned to its original position with the same speed and kept there for 10 seconds for relaxation. This process was continued until the completion of 20 cycles. The whole process of RTC test was also video recorded and the photos were extracted from the video. Finally, the Poisson's ratio values at tensile strains of 5%, 10%, 15%, 20% and 25% were calculated for each tensile cycle. Three replicates were tested in each tensile direction.

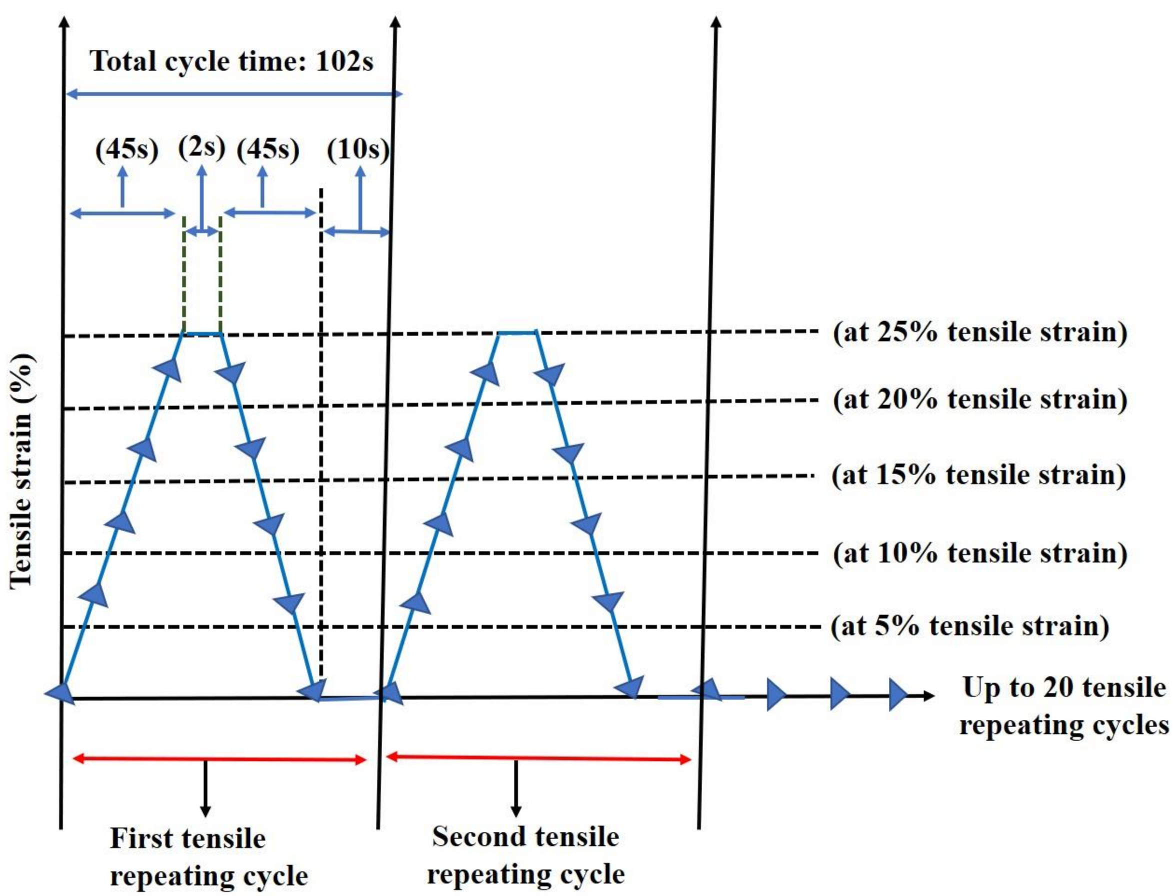

Figure 5. Process of RTC test at different tensile direction for 20 cycles

3. Results and discussion

3.1 The NPR effect of the auxetic woven fabric in different tensile directions

Upon relaxation, section C has the highest level of loose weave effect. Therefore it shows the excellent elasticity and higher shrinkage. On the other hand, section A also has shrinkage effect but smaller than section C and larger than section B. Since section B is placed between section C and section A, upon relaxation the edges of section B are folded in a diagonal fashion due to shrinkage difference of the other two sections, thus creating the approximation of REHG unit cell. When this structure is stretched, the folded diagonal ribs get flat and move towards straight form because of the reversal of shrinkage at section C, which leads to an increase of the dimensions in transverse directions. As a result, the dimensions of the whole structure is increased, and the NPR effect is achieved. Figure 6 shows a comparison of the Poisson's ratio-tensile strain curves, when the fabric is stretched along different tensile directions. It is can be seen that the NPR effect is produced along each tensile direction. However, the NPR effect is higher along the two principal directions as compared to the three biased directions. The highest NPR values of -0.34 and -0.29 were obtained at tensile strains of 3-6% along the warp and weft directions, respectively. With further stretching of the fabric, the NPR effect in both the principal directions rapidly decreases to -0.07 up to a tensile strain of 30%. After that, the NPR effects in the weft direction gradually decrease to zero up to a tensile strain of 93%. In the warp direction, the NPR effect first remains the same over a small range of tensile strain, then increases up to a tensile strain of 62% with the NPR values from -0.07 to -0.1. Afterwards, the NPR effect decreases continuously and becomes zero up to a tensile strain of 90%. These results indicate that the fabric has the NPR effect over a large range of tensile strain in both the principal directions. On the other hand, as shown in Figure 6, the NPR effect is also produced when the fabric is stretched along three biased directions. However, the NPR effect is only achieved over a smaller range of tensile strain as compared to the principal directions. In this case, the NPR effect reaches its highest level at the initial stage of tensile strain, and gradually decreases to zero and becomes positive with the increase in tensile strain. The highest NPR value of -0.14 is obtained at a tensile strain of 4% when the fabric is stretched along the 67.5° biased direction, and the lowest NPR effect is produced when stretched along the 22.5º biased direction. While the NPR effect is only kept up to a tensile strain of 18% when stretched along biased directions 22.5º and 45º, the NPR effect can be produced up to a tensile strain of 34% when stretched along 67.5º biased direction. It is necessary to mention that the Poisson's ratio is only measured up to the tensile strain level when its value is still negative. In all the tensile directions, the NPR of the fabric greatly increases at the beginning of tensile strain increase but it decreases with the further increase of tensile strain. The main reason for this behavior is that the achieved REHG structure in fabric is in a foldable form. Its NPR effect greatly increases due to opening of the REHG structure at smaller tensile strain. However, with the increase of tensile strain, opening effect decreases, resulting in lower NPR effect.

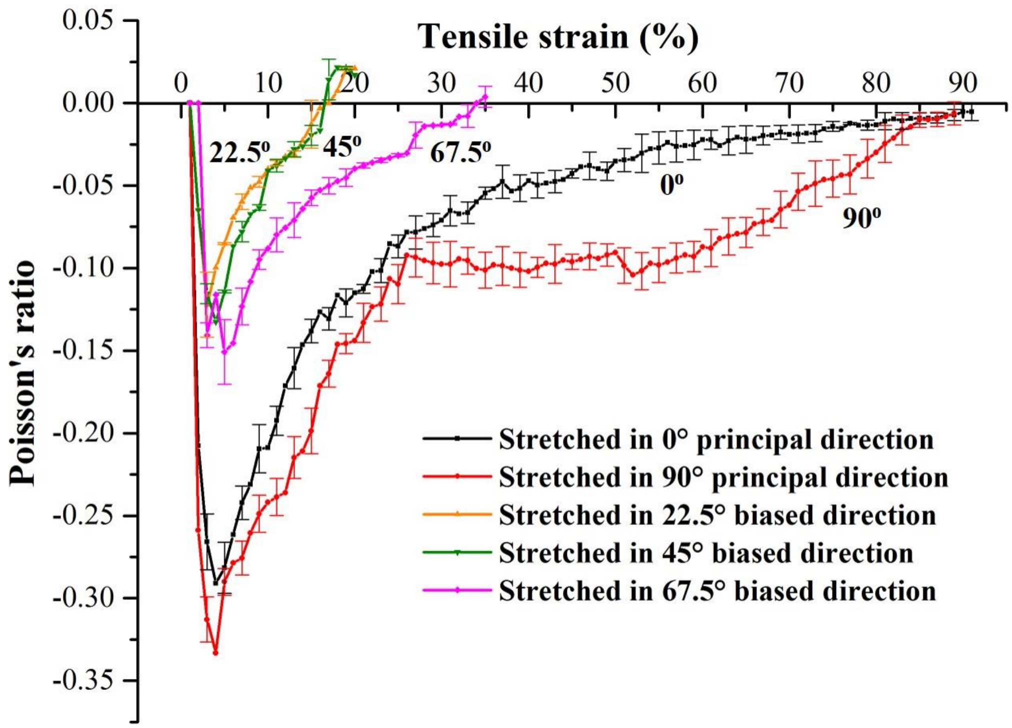

Figure 6. Poisson's ratio-tensile strain curves of the auxetic woven fabric in different tensile directions.

As explained above, the fabric shows larger NPR effect over a larger range of tensile strain in both principal directions throughout the tensile loading tests. Conversely, smaller NPR effect is achieved over a smaller range of tensile strain in all three biased directions. The reason for this behavior is that the unit cell of REHG structure has its two sides along two principal directions, that is, the long side is aligned along the warp direction and the short side along the weft direction. Since the NPR effect is purely linked to the geometrical orientation of the unit cell, stretching along the principal directions makes the structural unit cell to deform more straightforwardly and obviously in tensile as well as in transverse direction as shown in Figure 7. This results in larger expansion in the transverse direction and a larger NPR effect is produced. On the other hand, when the fabric is stretched along biased directions, the real orientation of the REHG structure unit cell is misplaced and is not aligned with the tensile direction as shown in Figure 8. Therefore, the deformation of the unit cell in tensile and transverse direction is not straightforward and obvious. This results in smaller expansion in the transverse direction producing smaller NPR effect only over a small range of tensile strain.

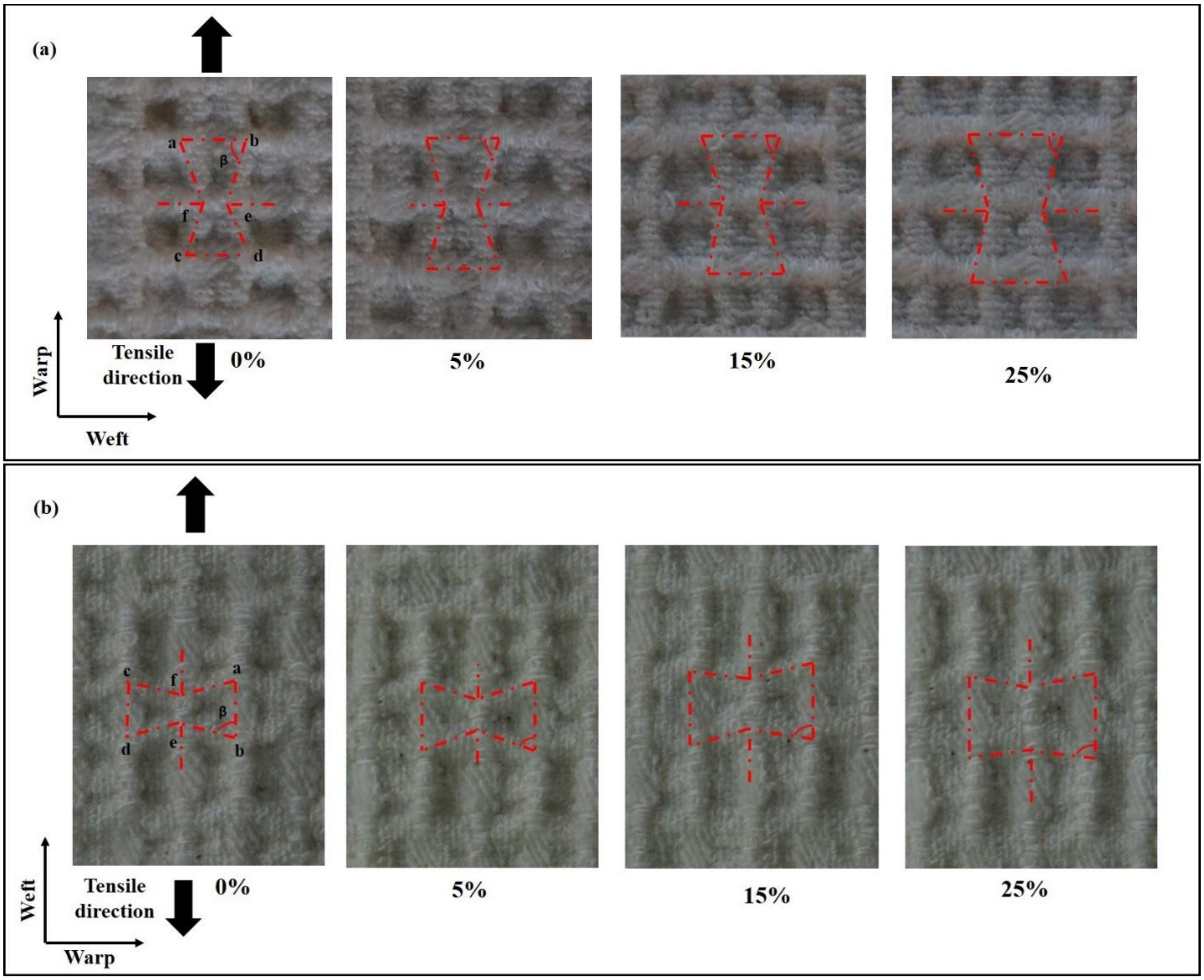

Figure 7. Photos of specimens in two principal tensile directions showing the deformation of the unit cell at different percentage of tensile strain: (a) warp direction; (b) weft direction.

In addition, it is worth mentioning that the re-entrant structure has two axes of symmetry such that application of tensile load parallel to the axes of symmetry does not produce shearing. Application of tensile load in the off-axis direction produces overall or global shearing to the entire fabric provided that the tensile testing fixtures are permitted to move sideways. Since the fixtures can only move vertically, the shearing is local and the global shearing to the entire fabric is restricted. This behavior contributes to an NPR effect in a narrow strain range from 0 to 35% or less when the tensile load is applied in the biased directions.

Moreover, from Figure 6, it can be observed that when the fabric is stretched along a biased direction that is closer to any one of the two principle directions, the NPR effect is also closer to that produced in that principle direction. Therefore, a larger NPR effect over a larger tensile strain is achieved when the fabric is stretched along 67.5° biased direction as compared to that produced when the fabric is stretched along 22.5° and 45° biased direction. This is because this direction is closer to the warp direction which produces the highest NPR effect. Similarly, smaller NPR effect over a smaller range of tensile strain is achieved when the fabric is stretched along 22.5° biased direction as compared to that produced when the fabric is stretched along 45° and 67.5° biased direction. This is because this direction is closer to the weft direction which produces smaller NPR effect than in the warp direction. In addition, it can be observed from Figure 6 that when the fabric is stretched along 45° biased direction, the NPR effect produced is between the NPR effects produced when the fabric is stretched along 22.5° and 67.5° biased direction. Since this tensile direction is not closer to any of the principal tensile direction, the fabric therefore has a unique behavior in this tensile direction which is not closer to either of the principal tensile direction.

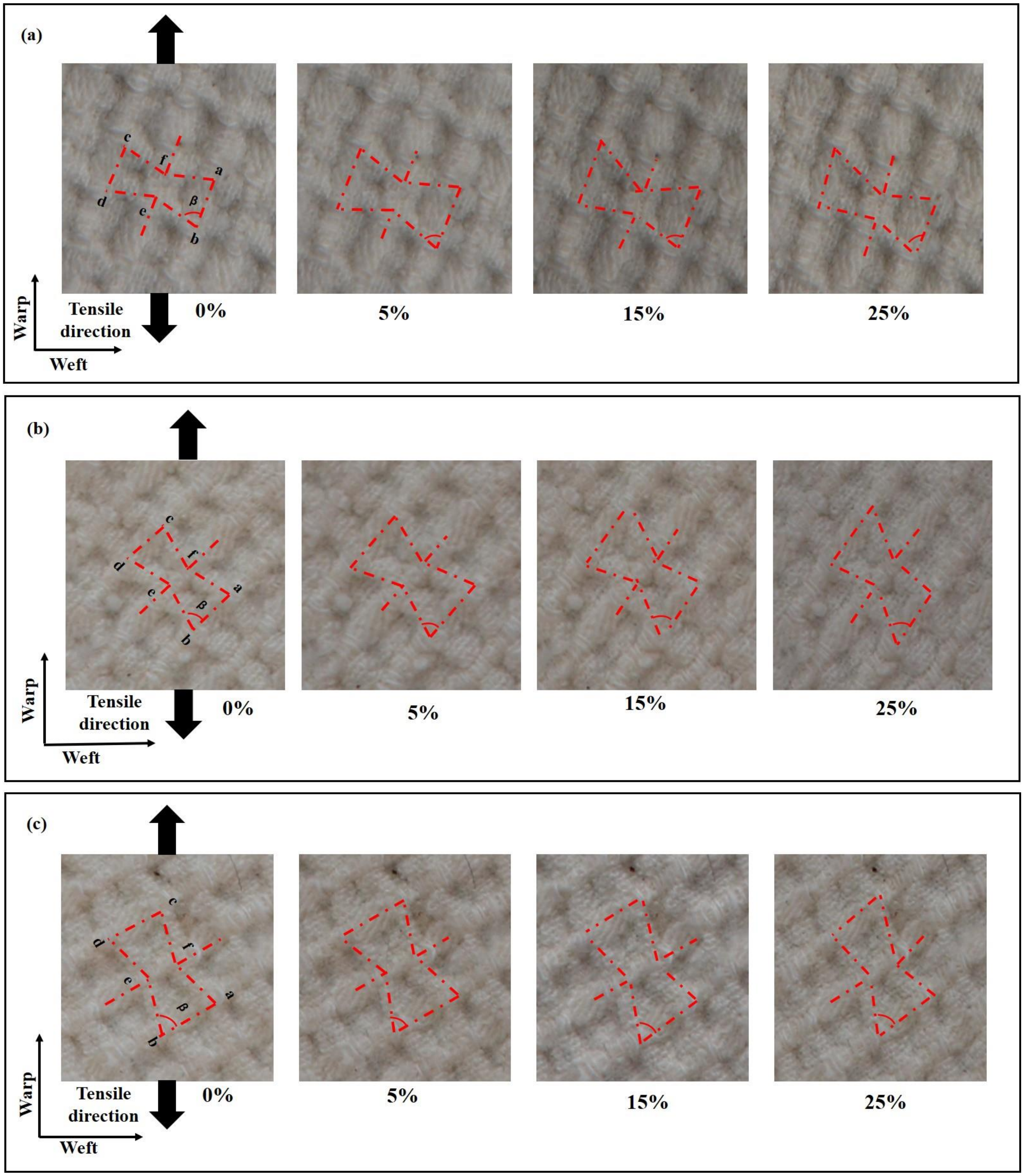

Figure 8. Photos of specimens in three biased tensile directions showing the deformation of the unit cell at different percentage of tensile strain: (a) 22.5° biased direction; (b) 45° biased direction; (c) 67.5° biased direction.

In addition to the orientation of the fabric structural unit cell, the NPR effect is also influenced by the fabric extensibility in different tensile direction. Figure 9 shows the tensile stress-tensile strain curves of the fabric in different tensile directions. When stretched in biased directions, the fabric has more extensibility as compared to the warp direction. In this case, the magnitude of tensile strain depends on the deviation of the tensile direction to the warp direction. This is because stretching the fabric in biased directions can result in three different conditions that are associated with warp yarns. Firstly, both ends of the yarns in tensile direction are clamped, secondly only one end is clamped and lastly both ends of the yarn are free for extension. Therefore, upon stretching in a biased direction that is more away from warp direction, the existence of the second or third conditions becomes more obvious and the extensibility is increased. Consequently, there is very little tension in the yarns and the maximum elongation occurs along the direction of applied force. Because of this, the straightforward deformation of REHG structural unit cell is very less and a smaller NPR effect is produced. This is also evident from the fabric photos taken at different tensile strains when the fabric is stretched in biased direction as shown in Figure 8.

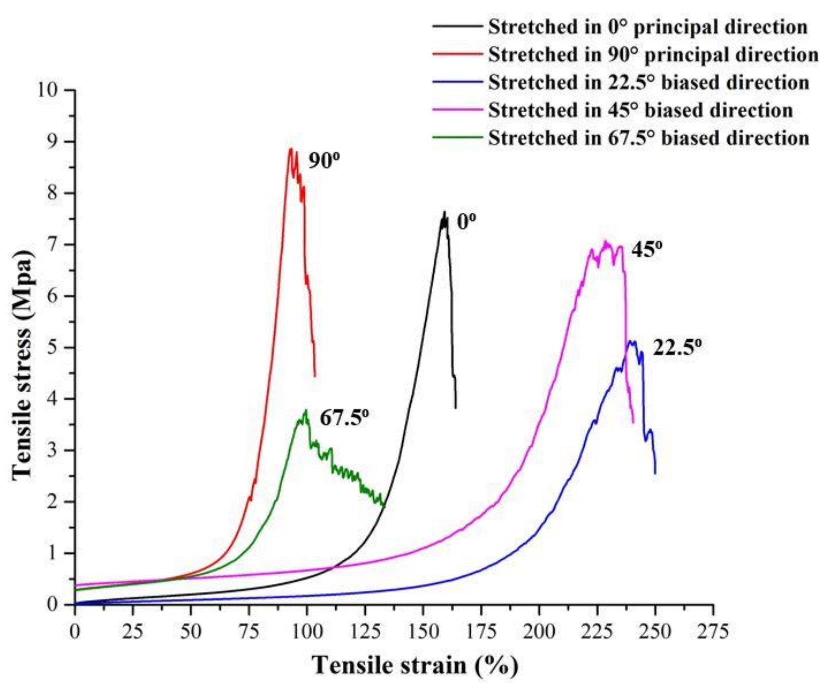

Figure 9. Tensile stress-tensile strain curves of the auxetic woven fabric in different tensile directions.

3.2 The NPR effect of the auxetic woven fabric under repeated tensile conditions in different tensile directions

To show the influence of RTC and tensile direction on the NPR effect, plots of Poisson's ratio as a function of tensile cycle at tensile strain of 5%, 10%, 15%, 20% and 25% for each stretch direction are presented in Figure 10. From Figure 10(a-e), it can be seen that for each stretch direction and for each level of tensile strain, the highest NPR value is obtained after the first RTC, and the NPR value decreases with increasing RTC. When the fabric is stretched in the warp direction, the highest NPR value of -0.31 is achieved at tensile strain of 5 % after the first RTC. Afterward the NPR effect is decreased after every tensile cycle up to the ten RTC, then the NPR effect is kept almost same up to twenty RTC. However, it is found that the fabric can keep 47-52% of the NPR effect after completing twenty RTC for each level of tensile strain. In the weft direction, specimen shows the highest NPR value of -0.28 at tensile strain of 5 % after the first RTC. It is found that the NPR value is almost same from eleven RTC to twenty RTC for each level of tensile strain except 25% at which the NPR effect is lost completely after the fifteen RTC. However, the fabric can keep 40-55% of the NPR effect after completing twenty RTC.

Moreover, when the fabric is stretched in 22.5° biased direction at tensile strain of 5 %, a lowest NPR value of -0.08 is obtained. The NPR value is decreased until six RTC. After that, the NPR values is kept until ten RTC. When the fabric is stretched in 45° biased direction, the NPR effect decreases with increasing RTC until fifteen RTC, after that the fabric produces positive Poisson's ratio. Lastly, when the fabric is stretched in 67.5° biased direction, an NPR value of -0.15 is obtained at tensile strain of 5 %. The NPR effect is still kept at the twenty RTC. At tensile strain of 10-15%, when the fabric is stretched in 22.5° and 45° biased direction, a smaller NPR effect is achieved after the first RTC and decreases with increases of RTC. The NPR effect is kept only until seven RTC except in case of stretching in 45^0 biased direction at tensile strain of 10% where the NPR effect is kept until thirteen RTC. In case of stretching along 67.5^0 biased direction, a larger NPR value of -0.12 is obtained after first RTC at 10 % of tensile strain and a smaller NPR of -0.07 is achieved at tensile strain of 15%. However, the NPR effect is retained until fifteen RTC. At 20-25% of tensile strain, upon stretching in 22.5^0 and 45^0 biased directions, no NPR effect is obtained, and the Poisson's ratio is positive even after first RTC. The NPR effect decreases with increasing RTC. In case of stretching in 67.5^0 biased direction, a smaller NPR is produced after the first RTC. The NPR effect is then lost completely after ten RTC at tensile strain of 20% and after seven RTC at tensile strain of 25%.

From the above results, it can be found that the NPR effect is largely dependent upon the stretching direction and number of RTC. It is also found that a higher NPR effect is produced when the fabric is stretched along the principal directions as compared to the biased directions. In addition, the NPR effect retention ability of the fabric is also higher in the principal directions as compared to biased direction. Moreover, between the two principal directions, the NPR effect and retention ability along the warp direction is higher as compared to the weft direction. This behavior is due to the fact that the REHG structure unit cell is more stable along the warp direction and can keep its shape even after the completion of many RTC. On the other hand, in case of weft and biased directions, nevertheless the fabric has higher extensibility along these directions but the REHG structure unit cell is not very stable and loses its shape. Therefore, the loss of NPR effect is higher along these direction as compared to the warp direction. The results of RTC test also show that the NPR effect is largely influenced by the number of tensile cycles and is decreased after many RTC for each stretch direction because there are always some permanent deformations induced in to the fabric structure after every RTC.

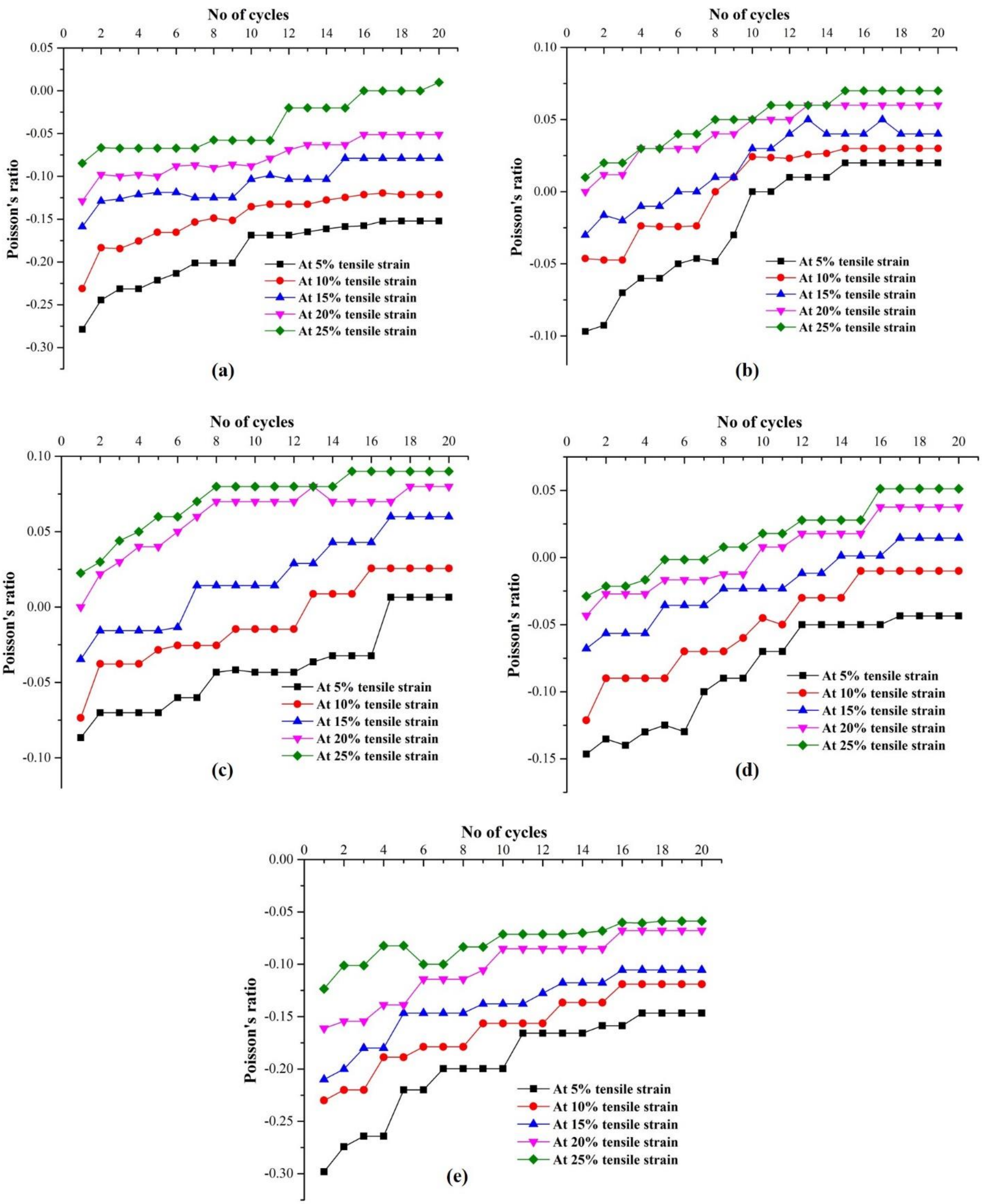

Figure 10. The influence of RTC and tensile direction on the NPR effect: (a) stretched in weft direction (0°); (b) stretched in biased direction (22.5°); (c) stretched in biased direction (45°); (d) stretched in biased direction (67.5°); (e) stretched in warp direction (90°).

4 Conclusions

A systematic study on the NPR effect of the auxetic woven fabric based on the REHG structure in different tensile directions under single and repeated cycles is reported in this paper. From this study, the following conclusions can be drawn.

1. The NPR effect of auxetic woven fabric is dependent on the tensile direction. The NPR effect is higher when the fabric is stretched along the principal directions than that when fabric is stretched along biased directions.
2. Between the two principle directions, the higher NPR effect is achieved when the fabric is stretched along the warp direction.
3. When the fabric is stretched in the biased directions, a smaller NPR effect is produced due to less straightforward deformation of REHG structural unit cell.
4. Among three biased directions, the higher NPR effect is achieved when the fabric is stretched along 67.5° biased direction and the lowest NPR effect is achieved when the fabric is stretched along 22.5° biased direction.
5. The NPR effect of the auxetic woven fabric in each stretch direction decreases with increasing tensile cycles and the NPR effect retention ability of the fabric is higher in principal directions than in biased directions.

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