This is the accepted version of the publication Shuaiquan Z, Yuping C, Yadie Y, Minglonghai Z, Kamrul H, Hong H. Auxetic behavior of warp knitted fabric under repeating tension. Textile Research Journal. 2021;91(15-16):1732-1741. Copyright © 2021 (The Author(s)). DOI:10.1177/0040517521989277.

Auxetic behavior of warp knitted fabric under repeating tension

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Abstract

In our previous study, a novel class of auxetic warp knitted fabrics were developed and their auxetic behaviors were studied under single tensile test. However, during daily use, the fabrics are usually subjected to repeating tension rather than single tension. Therefore, the durability of the fabrics' auxetic performance is of great importance. So far, the auxetic behavior of fabrics under repeating tension has not systematically been investigated. In this paper, we report a study on the auxetic behavior of warp knitted fabrics under repeating tension. All the fabric samples were subjected to a repeating tensile test within a tensile strain of 25% until 100 tensile cycles. The results show that the fabrics can keep their auxetic effect in both course and wale testing directions after 100 tensile cycles, and the auxetic effect in the wale direction retains longer under higher tensile strains than that under lower tensile strains with the increase of tensile cycles. The results also indicate that auxetic stability in the course direction is much better than that in the wale direction. We hope that this study can offer useful information to improve auxetic stability of auxetic fabrics for practical use.

Keywords: Auxetic fabric; Knitted fabric; Negative Poisson's ratio; Repeating tensile test

1. Introduction

Poisson's ratio of materials can be negative and materials with negative Poisson's ratio are known as auxetic materials [1, 2]. Unlike their conventional counterparts, auxetic materials laterally expand when stretched and laterally contract when compressed [3, 4]. As the auxetic behavior of materials is structure-dependent but scale-independent, auxetic materials from nanoscale and microscale[5-7] to macroscale[8, 9] have been extensively studied by researchers in various fields [10-13].

In the field of textiles, great interest has been shown in auxetic fabrics, and consequently, a lot of auxetic fabrics have been realized using knitting [8, 14-20], weaving [21-23], and non-woven [24] technologies. Due to the auxetic behavior of fabrics, a dome-shape can be easily formed, which makes auxetic fabrics quite suitable to fit human body curves to enhance comfort. Potential applications of auxetic fabrics include sportswear, smart bandages, blast curtain [16] and smart filters [25]. Compared with weaving, knitting technology is more suitable for developing novel auxetic structures due to their flexibility in fabric design and production. Liu et al. [8] studied auxetic weft knitted fabrics based on foldable structures which are formed by the zig-zag distribution of reverse loops and face loops. When stretched, the foldable fabric structures unfolded causing an increase in the lateral direction, thus showing auxetic behavior. Hu et al. [14] also proposed auxetic weft knitted fabrics with the foldable structure comprised of alternatively distributed rectangle zones of reverse loops and face loops. In the same research, they also developed another two auxetic weft knitted fabrics based on reentrant hexagons and rotating rectangles, respectively. All the fabrics they produced were proven to be auxetic under certain extension.

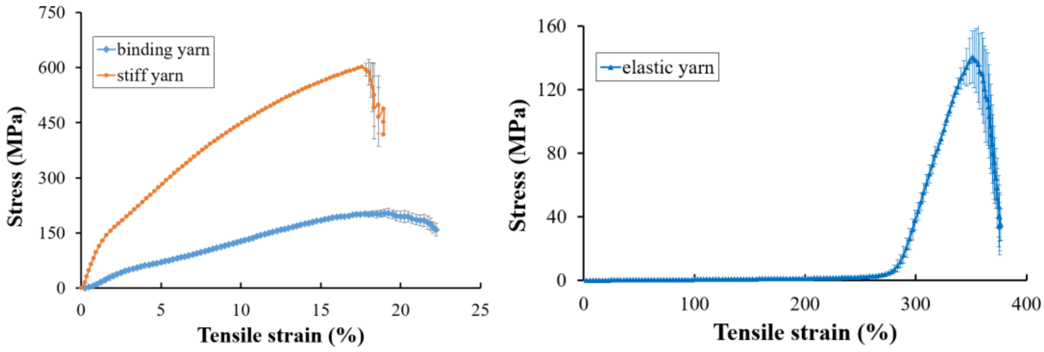
Regarding warp knitting, Ugbolue et al.[26] developed auxetic warp knitted fabrics by introducing elastic yarns into conventional hexagonal net to form reentrant hexagons. According to them, the structures could exhibit auxetic effect under stretch. Based on double arrowhead geometry, Alderson et al.[15] produced various auxetic warp knitted fabrics and studied the influence of knit pattern on the auxetic behavior. Their study showed that auxetic effect could be achieved along directions at ± 45° to the warp direction. Ma et al.[19, 27] fabricated another type of auxetic warp knitted fabrics based on rotational hexagonal structure using single needle bed and double needle bed warp knitting machines, respectively. Different from the above methods, Wang et al. [16] adopted an in-plane compression and heat setting process to fabricate auxetic warp knitted spacer fabrics to achieve good in-plane auxetic effect along both wale and course directions.

Although a number of auxetic fabrics have been developed and studied, most of the researches are limited to auxetic behavior under single tensile test. Only a few of studies were conducted on auxetic behavior of fabrics under repeating tension. Wang et al. [16] first studied auxetic behavior of warp knitted spacer fabrics under 10 repeating tensile cycles. Their study showed that auxetic effect decreased at the first several tensile cycles and then tended to keep constant. Hasan Kamrul et al. studied auxetic behavior of the woven fabrics based on re-entrant [28] and foldable geometries [29] in five different directions under 20 repeating tensile cycles. They found that negative Poisson's ratio decreased with the increase of tensile cycles and negative Poisson's ratio in the weft and warp directions showed better resilience to repeating tension. It should be pointed out that the previous studies are only limited within a small range of tensile cycles, which may not completely reflect auxetic behavior of fabrics in daily use because when those auxetic fabrics were used in daily life, it is more likely that they will be subjected to more times of repeating loads. Therefore, the study on auxetic behavior of fabrics in a wider range of tensile cycles is necessary. In the previous study[20], we have developed a novel type of auxetic warp knitted fabrics and studied their auxetic behavior in both the course direction and wale direction under single tensile test. In this paper, we extend our study to the auxetic behavior of the fabric under repeating tension within a much wider range of tensile cycles. We hope that this study can offer useful information to improve auxetic stability of auxetic fabrics for practical use.

2. Experimental details

2. 1 Preparation of fabric samples

As described in our previous study [20], the auxetic warp knitted fabrics were fabricated with three types of yarns: elastic yarn (116 dtex polyurethane (PU) yarn wrapped by polyester yarn), binding yarn (83 dtex polyester yarns) and stiff yarn (108 dtex polyester monofilament). The stress-strain curves of these yarns are shown in Figure 1.



(a) (b)

Figure 1 Stress-strain curves of the yarns used: (a) binding yarn and stiff yarn; (b) elastic yarns.

During the warp knitting process, elastic yarns were let-off with tension from warp beams to the knitting zone. Due to their low modulus shown in Figure 1 (b), they were extended very easily with applied tension during knitting process. When all the tension was released after knitting, the extended elastic underlaps shrunk causing the rotation of diagonal ribs to form re-entrant structures as shown in Figure 2 (a). When stretched in the wale direction, as shown in Figure 2 (b), diagonal ribs tend to turn along tensile direction causing the expansion of elastic underlaps, and as a result, the fabric exhibits an auxetic behavior. Table 1 shows structure details of the fabric used in this research.

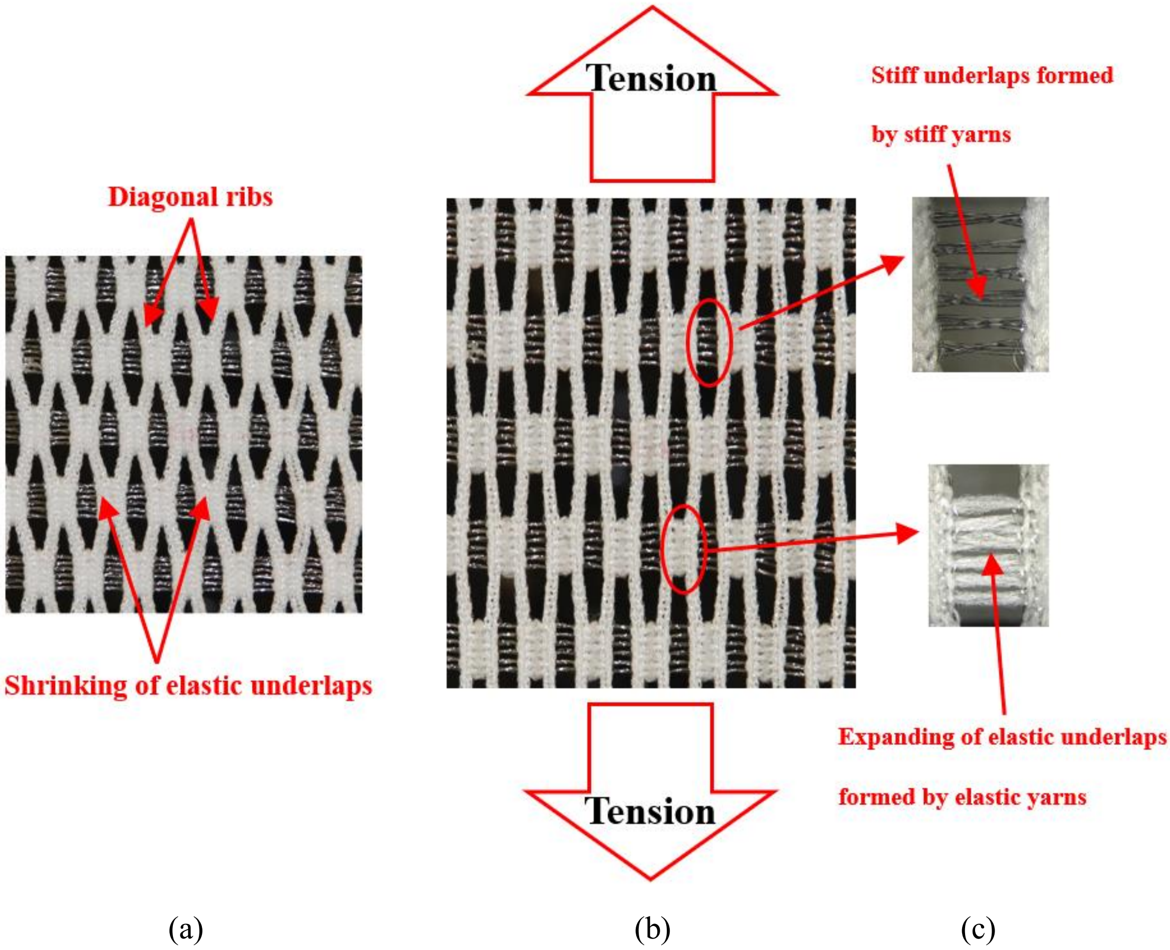


Figure 2 Photograph of the auxetic warp knitted fabric: (a) before stretch; (b) under tension in wale direction; (c) amplified underlaps.

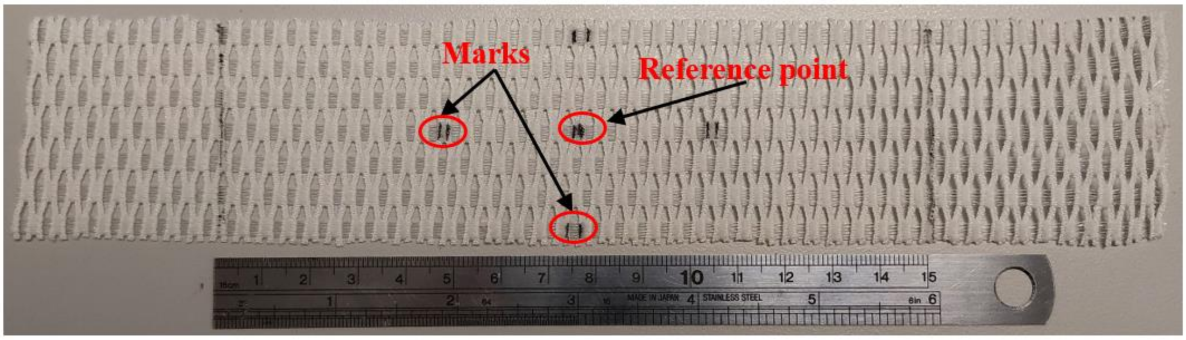
Table 1 Structure details of the fabric used

Chain notations	Threading details	CPC	WPC	Thickness (mm)
GB1:(1-0/0-1)*13//	GB1:2C,2K	22	8.4	0.64
GB2:(5-6/5-4)*3/ (5-6/1-0)*3/ (5-6/5-4)*4/ (9-10/5-4)*3//	GB2:1A, 3K,1 B,3K			
GB3:(5-4/5-6)*3/*(5-4/9-10)*3/(5-4/5-6)*4/(1-0/5-6)*3//	GB3:1B, 3K,1 A,3K			

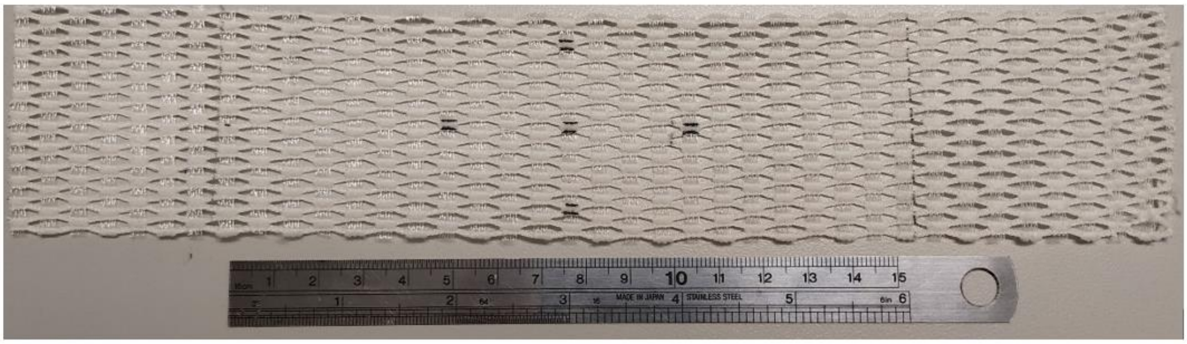
A: Elastic yarn; B: Stiff yarn; C: Binding yarns; K: Unthreading of yarns. CPC: Courses per centimeter; WPC: Wales per centimeter. GB1: The first yarn guide bar. GB2: The second yarn guide bar. GB3: The third yarn guide bar.

2.2 Repeating tensile test and calculation of Poisson's ratio

The repeating tensile test was conducted both in wale direction and course direction. Three samples were prepared for each direction. All the samples were cut into a size of 250 mm x 50 mm, as shown in Figure 3. Each sample was marked with five black points. The mark at the centre of the specimen was used as reference point and the other marks were made along the two sides of the reference point on the central line with a distance of 20 mm from the reference point in the lateral direction and tensile direction, respectively.



(a)



(b)

Figure 3 Samples prepared for testing: (a) cut along course direction; (b) cut along wale direction.

The repeating tensile tests were conducted by using an Instron machine with a gauge length of 150 mm. As shown in Figure 4, each specimen was tested for 100 tensile cycles. In each cycle, the specimen was firstly stretched with a speed of 50 mm/min till the tensile strain achieved 25%, then held for 2 seconds before the clamps returned to the original position with the same speed. Before the next tensile cycle, the sample was held in a relaxed state for 10 seconds.

During the test, a camera was set up to video-record the real-time deformation of the specimen under each tensile cycle. After the test, photos were extracted from videos with a time interval of 9 s, corresponding to an interval of 5% tensile strain. A screen ruler was used to measure the lateral length between two black marks vertical to the tensile direction in each photo.

The lateral strain ε_L was calculated using Eq. (1).

$$\varepsilon_L = \frac{X - X_0}{X_0} \qquad (1)$$

where X_0 is the original lateral length before the first stretch; X is the lateral length under stretch at given tensile strains.

With the calculated lateral strain ε_L and the given tensile strain ε_T, Poisson ratio ν was calculated from Eq. (2).

$$\nu = -\frac{\varepsilon_L}{\varepsilon_T} \qquad (2)$$

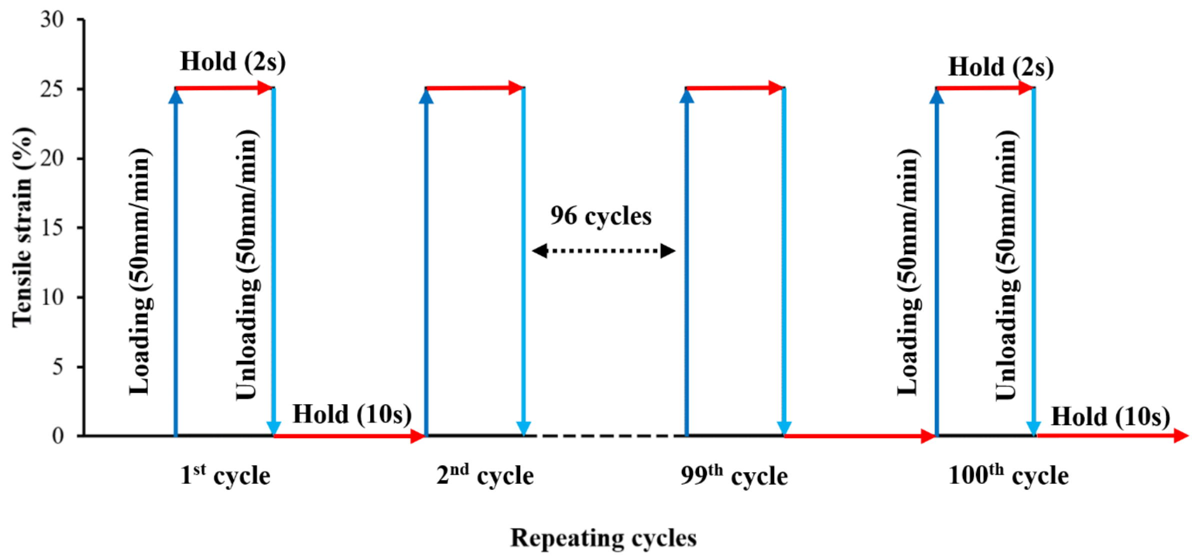


Figure 4 Schematic illustration of repeating tensile test

2.3 Calculation of residual deformation in each cycle

When the samples are loaded under abovementioned test conditions, they cannot recover completely in each tensile cycle due to the limited time given for relaxation. So, the term "residual deformation" is used here to demonstrate the nonreversible deformation of the fabrics after each tensile cycle. It only refers to the deformation that cannot be recovered under the abovementioned test condition. To understand auxetic behavior of fabric, it is necessary to analyze the residual deformation. Figure 5 illustrates a typical stress-strain curve of a repeating cycle, from which it can be seen that during the return process, the stress decreases. When the stress returns to 0 Mpa, tensile strain returns to A rather than its original position O. OA is the residual strain under the test condition, while OB is the total tensile strain. Then the residual deformation can be represented by the ratio of OA to OB.

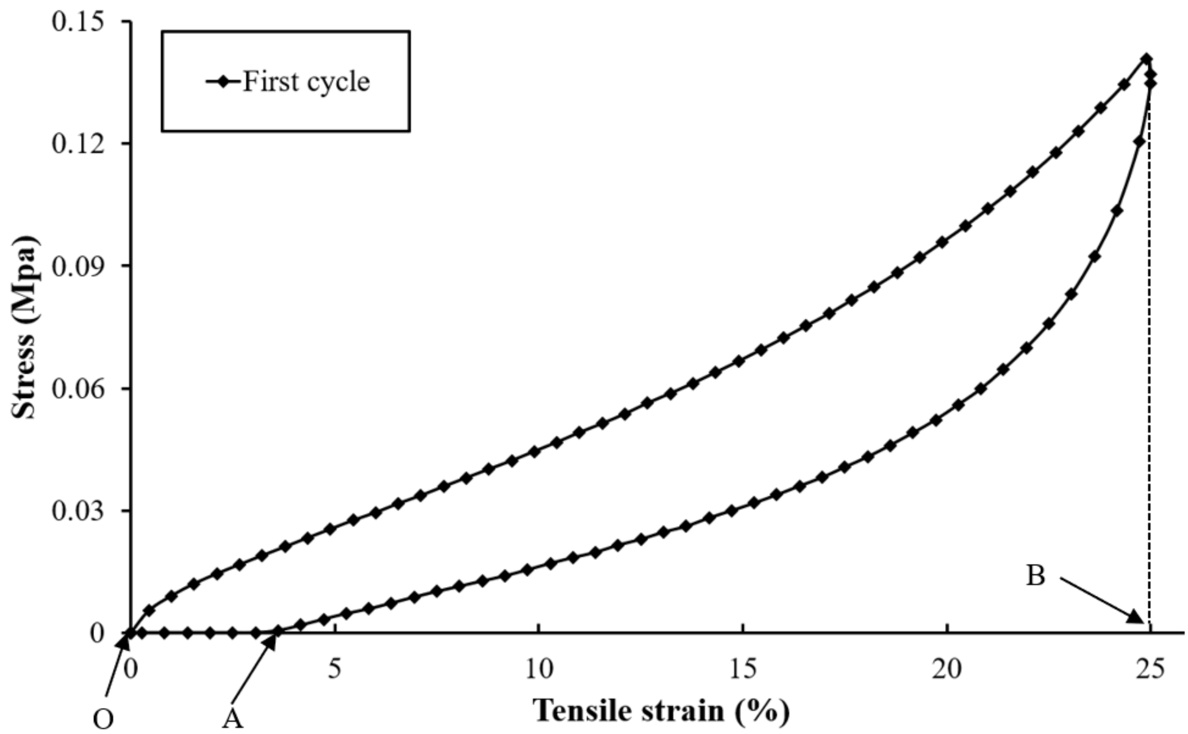


Figure 5 Stretch and recovery curve of the first cycle.

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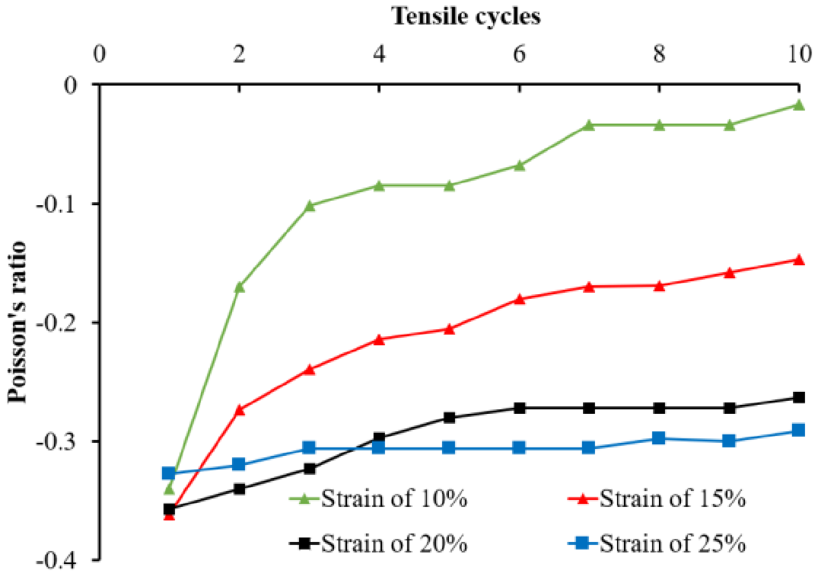
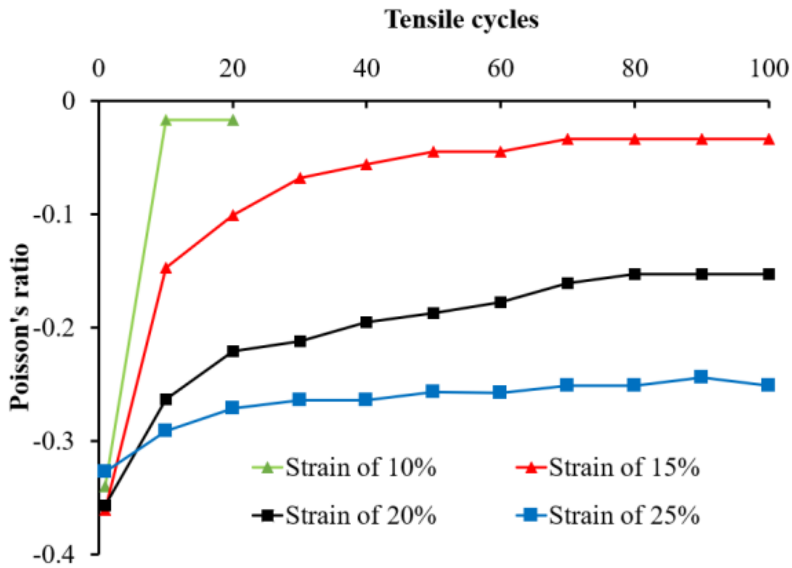
3. Results and discussion

3.1 Auxetic behavior in wale direction

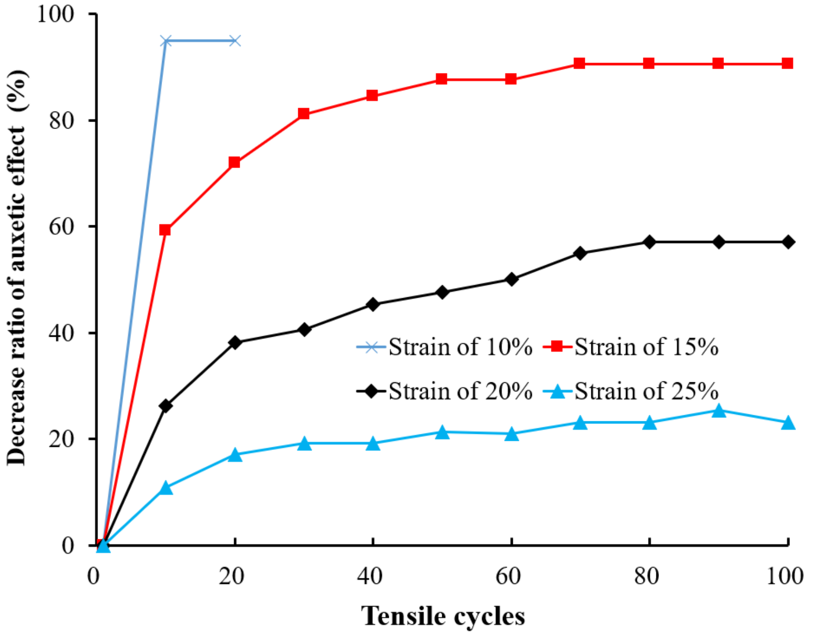
When the fabric is loaded in the wale direction, wales will bear the main force. Load exerted on wales will cause the rotation of diagonal ribs leading to the increase of fabric size in lateral direction. With the increase of tensile cycles, auxetic effect of the fabric varies. Figure 6 illustrates the influence of tensile cycles on auxetic effect of the fabric at different tensile strains. According to the results, the decrease of Poisson’s ratio mainly occurs during the initial several cycles. Figure 6 (a) is plotted using the results from the first cycle to the tenth cycle to show the variation of auxetic effect at the initial several tensile cycles, while Figure 6 (b) is plotted to show the overall results from the first cycle to the 100th cycle. Figure 6 (c) shows the decrease rate of Poisson's ratio in percentage with the increase of tensile cycles at different tensile strain levels. From Figure 6, the following phenomena can be observed: (1) the auxetic effect of the fabric shows good resilience to tensile cycles. Even after 100 times of repeating tension, the fabric still shows auxetic effect at all tensile strain levels; (2) with the increase of tensile cycles, auxetic effect of the fabric at all given tensile strains shows a decrease trend. In the first tensile cycle, the largest auxetic effect is found at tensile strain of 15% and the smallest auxetic effect is found at tensile strain of 25%. Within the first several tensile cycles, the auxetic effect decreases with a higher rate. However, after several times of stretch, the decreasing trend of the auxetic effect starts to slow down and the Poisson's ratio tends to be constant; (3) the influence of tensile cycles on auxetic effect of the fabric are different at different tensile strain levels. Poisson's ratio at lower tensile strain levels are more sensitive to tensile cycles compared to that at higher tensile strains. As shown in Figure 6 (c), at tensile strain of 10%, auxetic effect rapidly decreases and almost 90% of auxetic effect was lost after 10 times of stretch. On the contrary, at high level of tensile strains, for example at strain of 25%, after 100 times of stretch, only about 20% of the auxetic effect was lost; (4) after 20 times of stretch, the Poisson's ratio below strain of 10% cannot be measured because the residual deformation of the fabric becomes higher than 10%.


Tensile cycles
0
2
4
6
8
10
0
-0.1
-0.2
-0.3
-0.4
Poisson's ratio
Strain of 10%
Strain of 15%
Strain of 20%
Strain of 25%

(a)


Tensile cycles
0
20
40
60
80
100
0
-0.1
-0.2
-0.3
-0.4
Poisson's ratio
Strain of 10%
Strain of 15%
Strain of 20%
Strain of 25%

(b)



(c)

Figure 6 Decrease of auxetic effect at different tensile strains when stretched in wale direction: (a) tensile cycles from 1 to 10; (b) tensile cycles from 1 to 100; (c) decrease ratio of auxetic effect at different tensile strains with increase of tensile cycles.

The decrease in auxetic effect of the fabric under repeating tension in the wale direction can be explained by residual deformation. Figure 7 shows the residual deformation of the fabric in the wale direction as a function of tensile cycle. It can be seen that the residual deformation shows an obvious increase trend during the initial tensile cycles and then tends to be stabilized with the increase of tensile cycles. This variation trend is consistent with that of Poisson's ratio as shown in Figure 6. Under repeating tension, the deformation process of the fabric in each cycle can be divided into three stages. At the first stage, the deformation of the fabric mainly comes from the shape change of overlaps which can be fully recovered after release of load. With the increase of load, the second stage starts, where yarns start to transfer from underlaps to overlaps causing the increase of their length. The deformation of overlaps in this stage is largely prevented by chain stitches formed by the front bar and can be partly recovered after the release of load. In the third stage, yarns can no longer transfer and start to extend which cannot be recovered even after the load is released. Figure 8 shows the influence of the above three stages on fabric deformation in one repeating cycle, in which overlaps in one loop formed by binding yarn as shown in Figure 8 (a) was selected as an example. The relative positions of overlaps were marked in black. When the fabric is stretched, as shown in Figure 8(b), the shape of the overlaps becomes longer and thinner. With continuous increase of the tensile strain, yarns will transfer from adjacent loops. As shown in Figure 8 (a) and (c), the position of the black mark under the overlaps is different, which means the yarn is transferred and not able to return to its initial position when the tensile load is released. That is when residual deformation occurs. The increase of residual deformation reduces the rotation of diagonal ribs and decreases the lateral expanding. As a result, auxetic effect of the warp knitted fabric decreases with the increase of residual deformation. For a given tensile cycle, although the residual deformation at different tensile strains is nearly the same, it owns different influence on auxetic effect at different tensile strains. The lower the tensile strain is, the larger the influence will be. Therefore, for a given tensile cycle, the lower the tensile strain is, the faster auxetic effect decreases. Due to the increase of residual deformation with the increase of tensile cycles, for a given tensile strain, auxetic effect shows a decrease trend with the increase of tensile cycles.

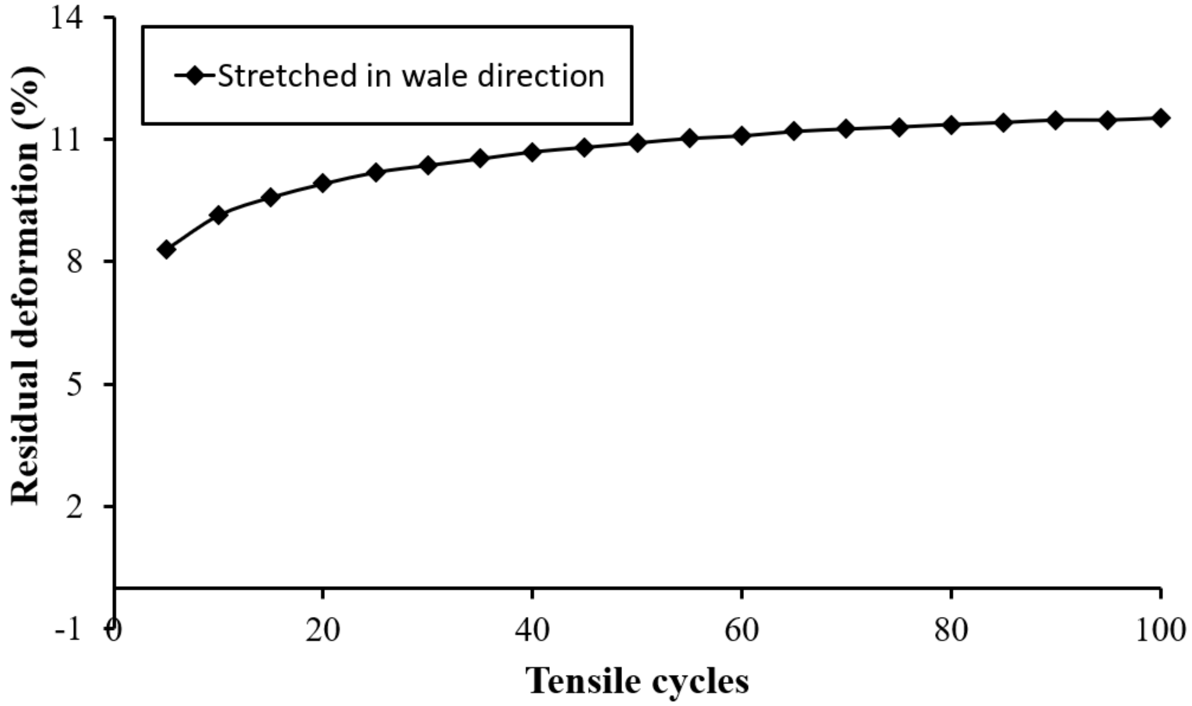
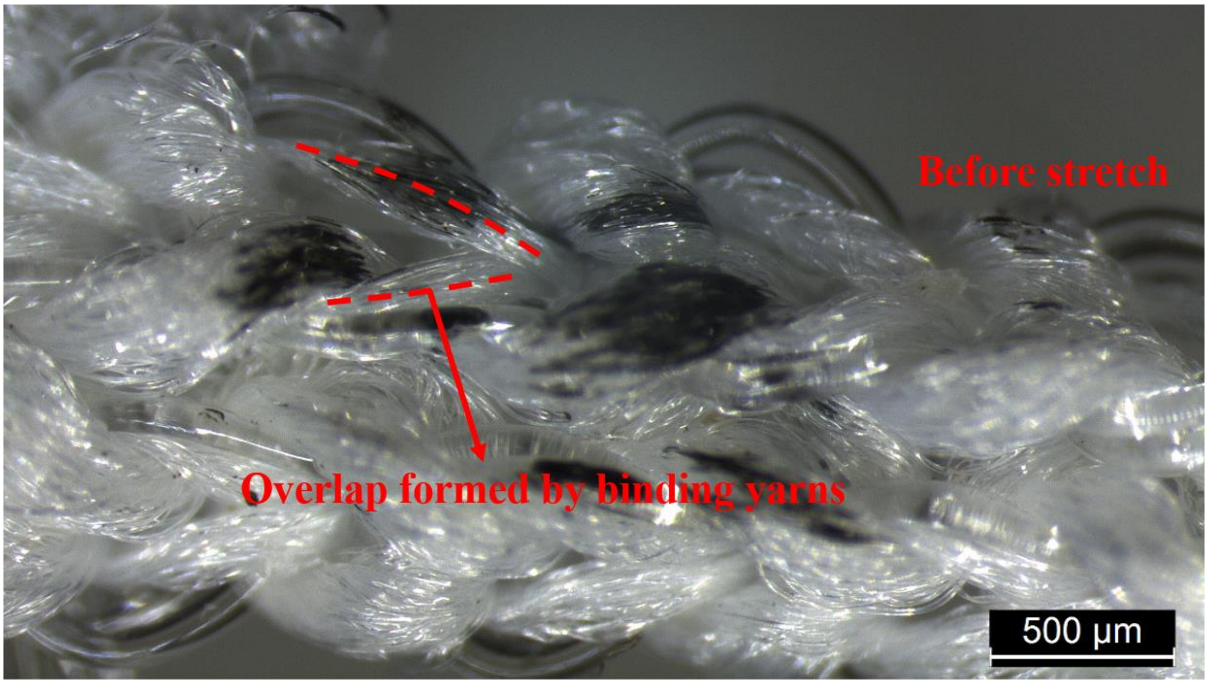
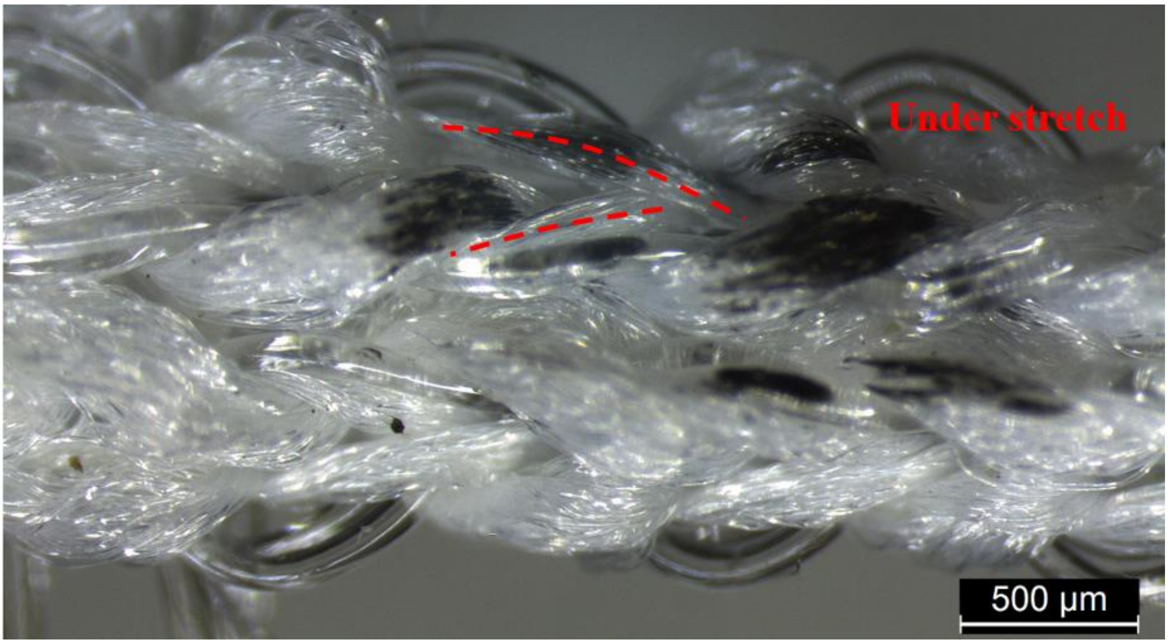


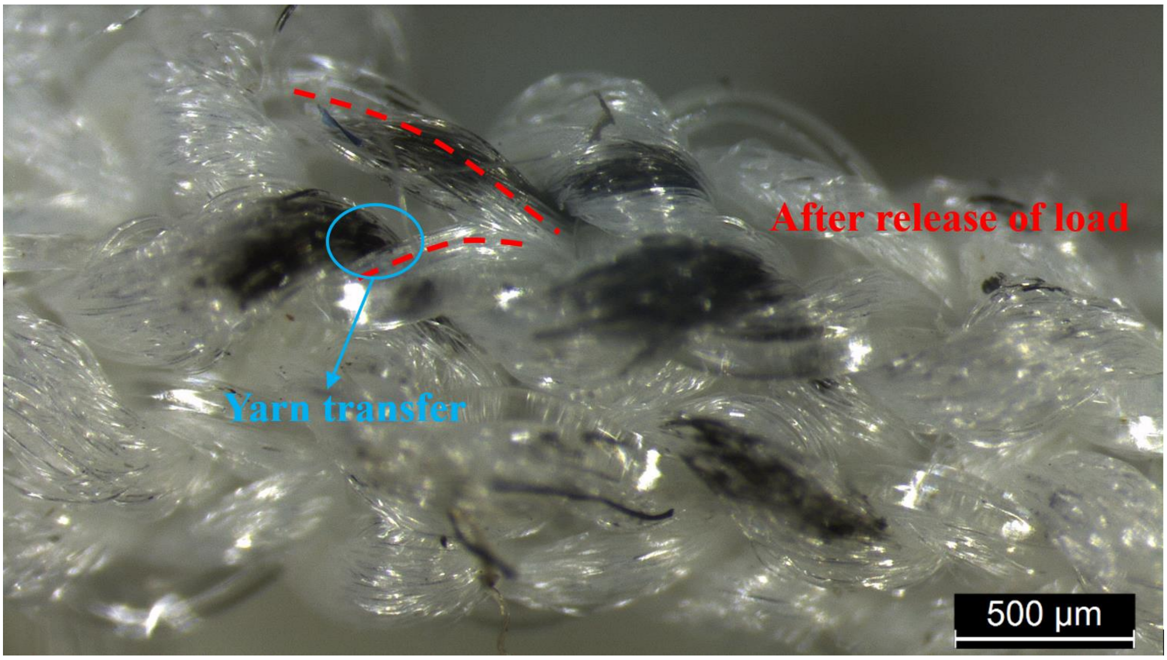
Figure 7 Residual deformation as a function of tensile cycle in wale direction with repeating tensile strain of 25%.


Before stretch
Overlap formed by binding yarns
500 μm

(a)


Under stretch
500 μm

(b)



(c)

Figure 8 Deformation of an overlap under repeating tension: (a) before stretch; (b) under stretch; (c) after release of load.

3.2 Auxetic behavior in course direction

When loaded in the course direction, due to the anisotropic property of the fabric structure, auxetic behavior is different from that in the wale direction. Figure 9 shows Poisson’s ratio of the fabric as a function tensile cycle at different tensile strains under tension in the course direction. From Figure 9, the following phenomena are observed: (1) within the tested tensile cycles, the fabric keeps auxetic effect at any given tensile strain. After 100 times of stretch, although the auxetic effect is lower than that in the wale direction, Poisson’s ratio of the fabric at all given tensile strains keeps negative. (2) at any given strains, auxetic effect of the fabric remains almost unchanged with the increase of tensile cycles. The auxetic effect when stretched in the course direction shows great resistance to repeating tension at almost all given tensile strains, except for the initial several tensile cycles at strain of 20%, where the auxetic effect slightly decreases with the increase of tensile cycles, and when tensile cycles are above 10, auxetic effect becomes constant. (3) for a given tensile cycle, the auxetic effect of the fabric shows an increase trend with the decrease of tensile strain except for strain of 10% where the auxetic effect is the same as that at strain of 15%.

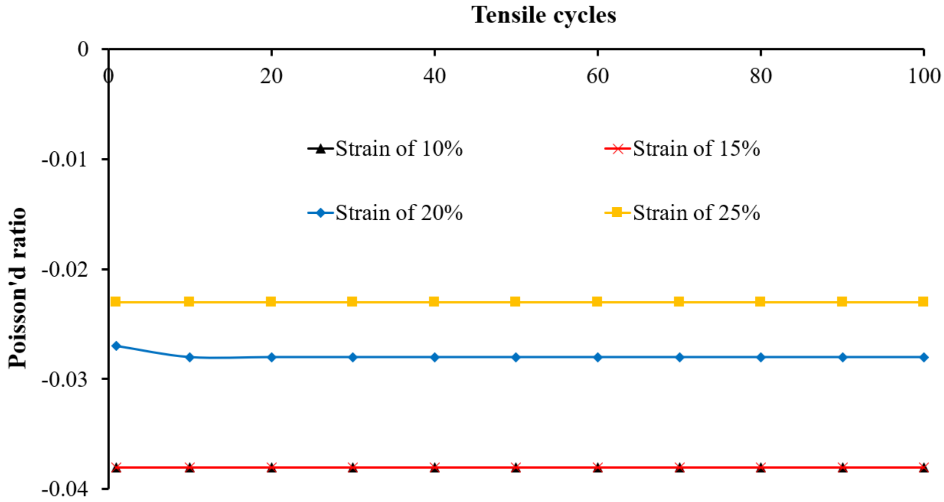


Figure 9 Poisson's ratio as a function of tensile cycle at different tensile strains under tension in course direction.

Under tension in the course direction, the underlaps of the fabric will bear the main force. With the increase of tensile strain, the load exerted on underlaps increases causing the extension of elastic underlaps. As stiff underlaps are not easy to be deformed, the extension of elastic underlaps will lead to the rotation of diagonal ribs, which results in an increase of fabric size in lateral direction. As a result, an auxetic effect exhibits.

Different from the tension in the wale direction, the fabric has much less residual deformation in the course direction. Figure 10 shows the residual deformation of the fabric as a function of tensile cycle under repeating tension in course direction. It can be seen that with the increase of tensile cycle, the residual deformation keeps below 5%, except the minor variations in the first several cycles. The deformation of the fabric in the course direction can also be divided into three stages. At the first stage, the deformation of the fabric mainly comes from the extension of elastic underlaps which can be fully recovered after release of load. When elastic underlaps are stretched to the same length of stiff underlaps, the second stage starts where both stiff and elastic yarns will transfer from loops to underlaps which may not be fully recovered even the load is released. In the third stage, the yarns cannot transfer any longer and they will be permanently stretched forming residual deformation.

Figure 11 shows deformation of underlaps under repeating tension in a repeating cycle. As shown in Figure 11 (b), when the fabric is stretched, elastic underlaps are extended from their shrinking state as shown in Figure 11 (a). When load is released, as shown in Figure 11 (c), the extended elastic underlaps return to their original length and no obvious residual deformation is observed. As for the loops, no obvious shape change or yarn transfer is observed neither. Therefore, within the strain of 25%, deformation of the fabric mainly comes from the first stage and the other two stage are less likely to happen. As a result, residual deformation almost keeps unchanged in course direction, and its effect on auxetic behavior is not evident. Therefore, Poisson's ratio is almost kept constant under repeating tension in course direction.

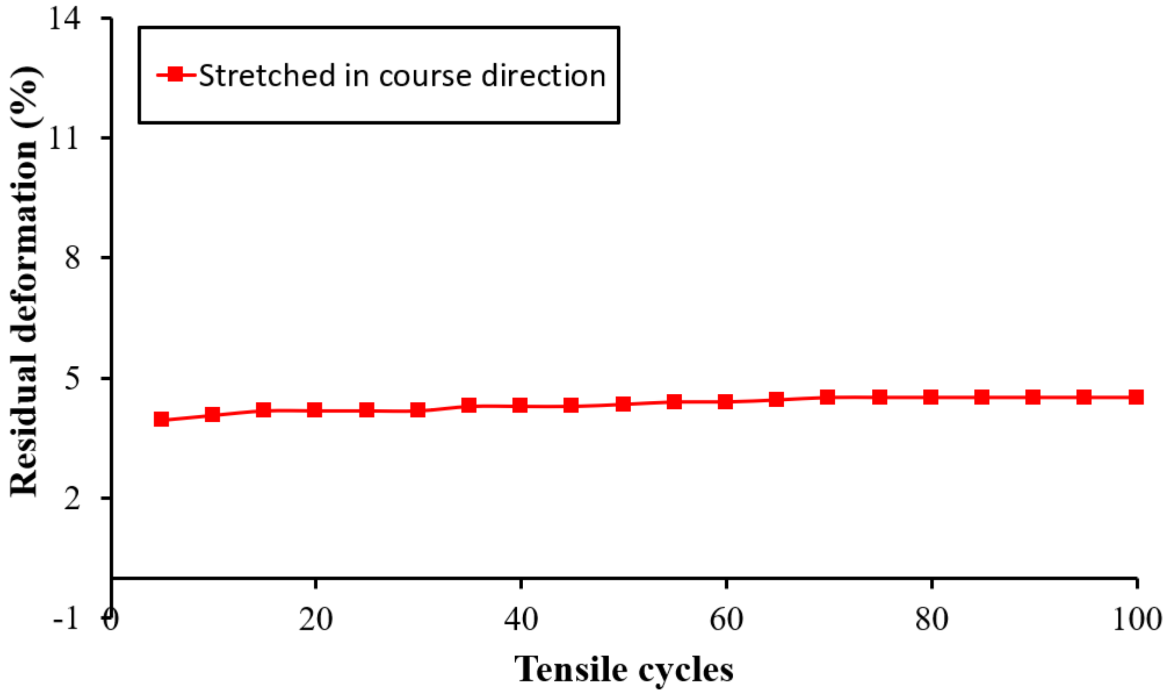
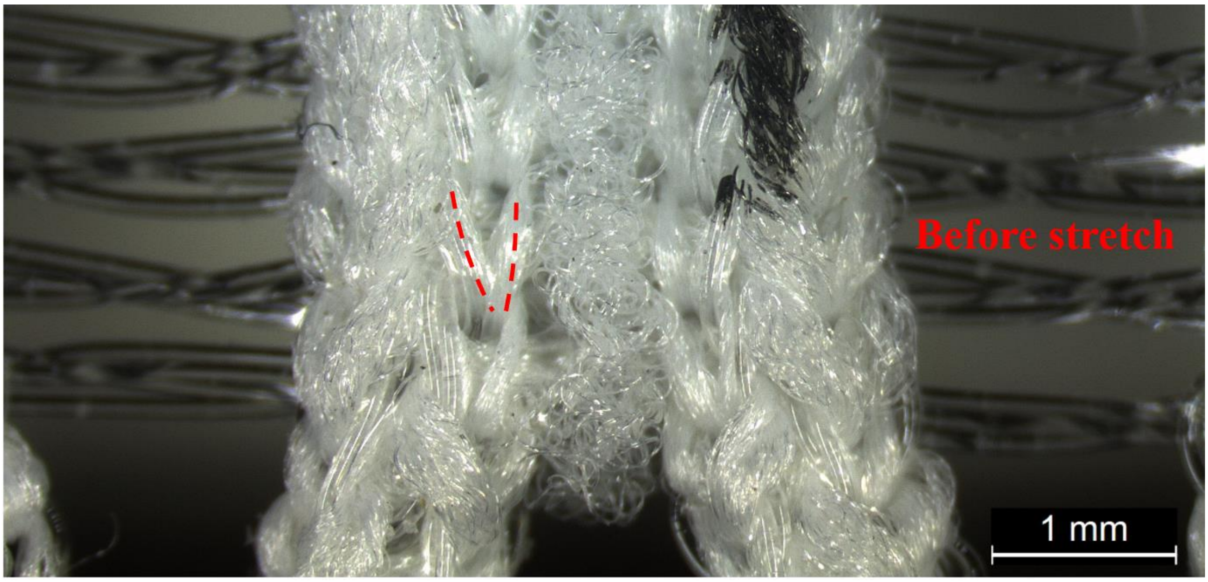
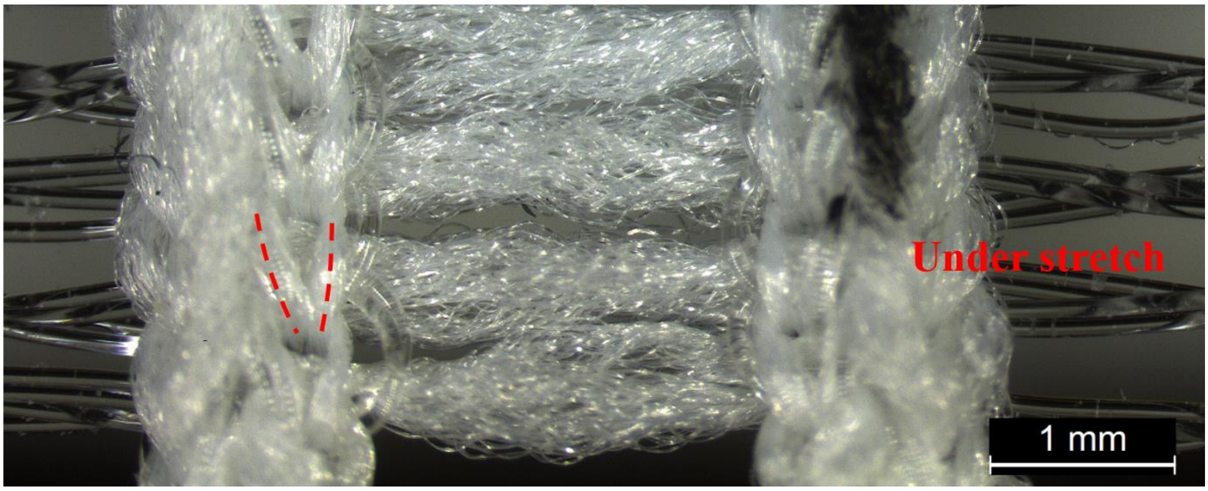


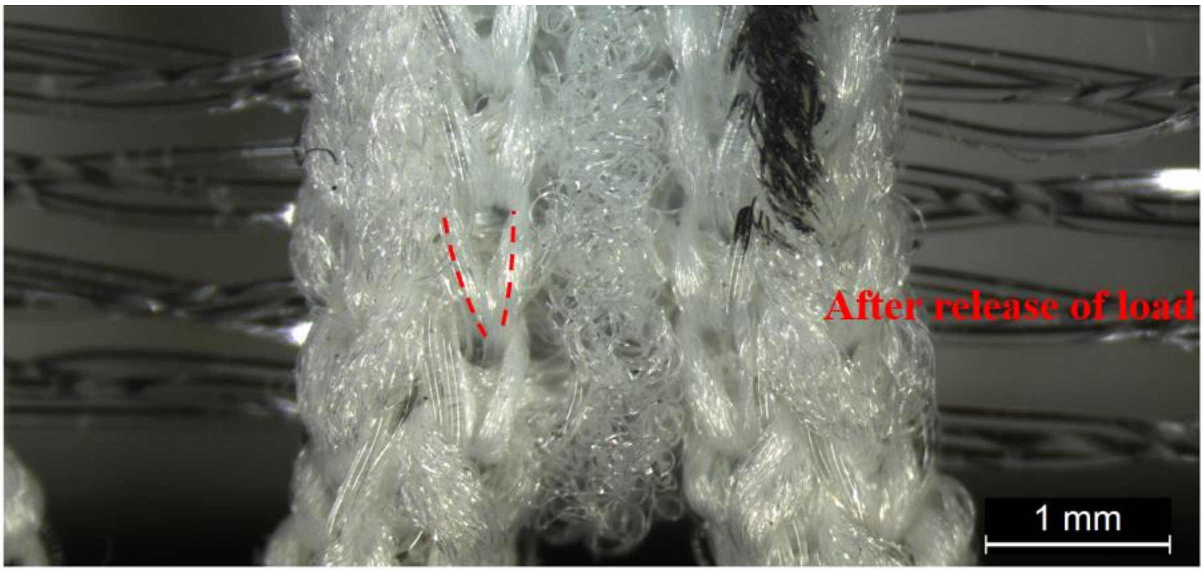
Figure 10 Residual deformation as a function of tensile cycle in course direction with repeating tensile strain of 25%.


Before stretch
1 mm

(a)


Under stretch
1 mm

(b)


After release of load
1 mm

(c)

Figure 11 Deformation of underlaps under repeating tension: (a) before stretch; (b) under stretch; (c) after release of load.

4. Conclusions

Auxetic behavior of the warp knitted fabric under repeating tension was studied. Its deformation process both in the wale and course directions was analyzed and the effect of residual deformation on auxetic behavior of the fabric was discussed. The following conclusions can be drawn from this research:

(1) The fabric proposed shows good auxetic stability under the given test condition. Even after 100 times of stretch with a tensile strain of 25%, the fabric can still keep an auxetic effect in both the course and wale directions.

(2) Auxetic effect in the wale direction is higher than that in the course direction, but less auxetic stability. The underlaps formed with elastic yarns contributes to the better auxetic stability in the course direction due to lower residual deformation.

(3) The residual deformation mainly comes from yarn transfer among loops and yarn extension. The use of elastic yarns can reduce the residual deformation of the fabric under given tensile strain and thus increase the stability of auxetic behavior.

Despite good results were obtained in this research with repeating tensile test of 100 cycles, the long-term durability of the auxetic fabric still remains unknown. Considering that most previous researches on auxetic property of fabrics mainly focused on single tensile cycle test, this paper can provide a reference value for the short-term auxetic persistence of fabrics. At the same time, it may also offer a reference to the long-term durability of the auxetic warp knitted fabrics in future study.

Acknowledgements

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

15209616). The authors would also like to acknowledge the helps from the Industrial Center of the Hong Kong Polytechnic University.

References

1. Lim, T.-C., *Mechanics of Metamaterials with Negative Parameters*. Springer Nature.
2. Lakes, R., *Composites and Metamaterials*. 2020: World Scientific.
3. Wang, Z. and H. Hu, *Auxetic materials and their potential applications in textiles.* Textile Research Journal, 2014. **84**(15): p. 1600-1611.
4. Hu, H., M. Zhang, and Y. Liu, *Auxetic textiles*. 2019: Woodhead Publishing.
5. Caddock, B. and K. Evans, *Microporous materials with negative Poisson's ratios. I. Microstructure and mechanical properties.* Journal of Physics D: Applied Physics, 1989. **22**(12): p. 1877.
6. Alderson, K. and K. Evans, *The fabrication of microporous polyethylene having a negative Poisson's ratio.* Polymer, 1992. **33**(20): p. 4435-4438.
7. Alderson, K., et al., *Novel fabrication route for auxetic polyethylene. Part 1. Processing and microstructure.* Polymer Engineering & Science, 2005. **45**(4): p. 568-578.
8. Liu, Y., et al., *Negative Poisson's ratio weft-knitted fabrics.* Textile Research Journal, 2010. **80**(9): p. 856-863.
9. Jiang, L., B. Gu, and H. Hu, *Auxetic composite made with multilayer orthogonal structural reinforcement*. Composite Structures, 2016. **135**: p. 23-29.
10. Scarpa, F., *Auxetic materials for bioprostheses [In the Spotlight].* IEEE Signal Processing Magazine, 2008. **25**(5): p. 128-126.
11. Duncan, O., et al., *Review of auxetic materials for sports applications: Expanding options in comfort and protection.* Applied Sciences, 2018. **8**(6): p. 941.
12. Yang, C., H.D. Vora, and Y.B. Chang. *Application of auxetic polymeric structures for body protection*. in *ASME 2016 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*. 2016. American Society of Mechanical Engineers Digital Collection.
13. Ungureanu, B., et al., *Auxetic-like metamaterials as novel earthquake protections.* arXiv preprint arXiv:1510.08785, 2015.
14. Hu, H., Z. Wang, and S. Liu, *Development of auxetic fabrics using flat knitting technology.* Textile Research Journal, 2011. **81**(14): p. 1493-1502.
15. Alderson, K., et al., *Auxetic warp knit textile structures.* physica status solidi (b), 2012. **249**(7): p. 1322-1329.
16. Wang, Z. and H. Hu, *3 D auxetic warp-knitted spacer fabrics.* physica status solidi (b), 2014. **251**(2): p. 281-288.
17. Glazzard, M. and P. Breedon, *Weft-knitted auxetic textile design.* physica status solidi (b), 2014. **251**(2): p. 267-272.
18. Ugbolue, S., et al., *Engineered warp knit auxetic fabrics.* J. Text. Sci. Eng, 2012. **2**(1).
19. Ma, P., Y. Chang, and G. Jiang, *Design and fabrication of auxetic warp-knitted structures with a rotational hexagonal loop.* Textile Research Journal, 2016. **86**(20): p. 2151-2157.
20. Zhao, S., et al., *Development of auxetic warp knitted fabrics based on reentrant geometry.* Textile Research Journal, 2020. **90**(3-4): p. 344-356.

21. Cao, H., et al., *Bi-stretch auxetic woven fabrics based on foldable geometry.* Textile Research Journal, 2019. **89**(13): p. 2694-2712.
22. Ng, W.S. and H. Hu, *Woven fabrics made of auxetic plied yarns.* Polymers, 2018. **10**(2): p. 226.
23. Zulifqar, A. and H. Hu, *Development of bi-stretch auxetic woven fabrics based on re-entrant hexagonal geometry.* physica status solidi (b), 2019. **256**(1): p. 1800172.
24. Verma, P., et al., *Inducing out-of-plane auxetic behavior in needle-punched nonwovens.* physica status solidi (b), 2015. **252**(7): p. 1455-1464.
25. Alderson, A., et al., *An auxetic filter: a tuneable filter displaying enhanced size selectivity or defouling properties.* Industrial & engineering chemistry research, 2000. **39**(3): p. 654-665.
26. Ugbolue, S.C., et al., *The formation and performance of auxetic textiles. Part II: geometry and structural properties.* The Journal of the Textile Institute, 2011. **102**(5): p. 424-433.
27. Chang, Y. and P. Ma, *Fabrication and property of auxetic warp-knitted spacer structures with mesh.* Textile Research Journal, 2018. **88**(19): p. 2206-2213.
28. Kamrul, H., A. Zulifqar, and H. Hu, *Deformation behavior of auxetic woven fabric based on re-entrant hexagonal geometry in different tensile directions.* Textile Research Journal, 2020. **90**(3-4): p. 410-421.
29. Kamrul, H., et al., *Deformation behavior of auxetic woven fabric made of foldable geometry in different tensile directions.* Textile Research Journal, 2020: p. 0040517520936289.