A Study of Woven Fabrics Made of Helical Auxetic Yarns

Yajie Gao¹ · Xiaogang Chen¹

Received: 13 May 2021 / Accepted: 30 July 2021 / Published online: 6 October 2021
© The Author(s) 2021

Abstract

The paper presents a study on woven fabrics made of helical auxetic yarns (HAYs) and their key factors on Poisson's ratio under tension. The work aims to create and evaluate auxetic woven fabrics with optimal parameters for achieving better auxeticity including weave structure, wrapping angle of the auxetic yarn, thickness of the auxetic yarn and properties of the warp yarn. The maximum negative Poisson's ratio (NPR) of the woven fabric can be achieved as low as -2.92 for experiments. Then, a numerical study has been carried out as well to assist the development of auxetic woven fabrics. The findings of this paper showed longer float length, lower wrapping angle of the auxetic yarn, a thinner diameter of the auxetic yarn as well as lower tensile modulus of the warp yarn led to higher auxetic behaviour. This can also provide a reference for researchers to select the best parameters for producing the auxetic woven fabrics.

Keywords Auxetic · Woven fabrics · Helical auxetic yarns · Negative Poisson's ratio

1 Introduction

Based on the elastic theory of the materials, Poisson's ratio is defined as the ratio between the longitudinal extension and transversal contraction of the material under tension. For most of the isotropic materials, the Poisson's ratio value is in the range of 0 to 0.5. For anisotropic materials, the Poisson's ratio value could be larger than 10 [1], whereas for auxetic materials, they are novel materials demonstrating negative Poisson's ratio [2]. Compared to conventional materials, auxetic materials exhibit superior properties which are suitable for achieving various potential material performances, such as shear resistance [2], indentation resistance [3], fracture resistance [4], synclastic behaviour [5], variable permeability [6] and energy absorption [7]. In the late nineteenth century, the natural materials exhibiting negative Poisson's ratio were reported by Voigt [8]. However, the auxetic materials were not drawn attention to many researchers until the auxetic foam was produced by Lakes [4] in 1987. Then, many auxetic materials and structures were reported in different field, such as cellular materials, microporous polymers, ceramics and composites [3].

✉ Xiaogang Chen
xiaogang.chen@manchester.ac.uk

¹ Department of Materials, School of Natural Sciences, The University of Manchester, Manchester M13 9PL, UK

In textiles, many researchers have discovered the auxetic behaviour from fibre [9–11] to fabric using different materials and structures. Auxetic fabrics can be made using conventional textile technologies including weaving [12, 13], knitting [14–16], braiding [17, 18] and nonwoven [19–21]. Auxetic woven fabrics attracted many researchers in recent years due to their integrated structure and dimensionally stable properties compared with other fabrics [22]. There are two main approaches to create auxetic woven fabrics. One is the use of non-auxetic yarns weaving into woven fabrics. Ali, Zeeshan [23] reported their study on different mechanical properties of auxetic woven fabrics compared with non-auxetic fabrics. The auxetic woven fabric was created using cotton yarns and elastic yarns. Then, honeycomb geometry was formed by the shrinkage behaviour of different weave structure. Some potential applications were reported as well including blast curtains, protective gloves and puncture tolerant composites due to its low initial modulus. They also reported the auxetic woven fabric can be considered for medical and wearable applications because it showed higher sensitivity and comfort properties [24]. Recently, auxetic woven fabrics based on geometric structures were developed, such as re-entrant hexagonal geometry [25] and foldable structure [26–28]. The combination of the elastic and non-elastic yarns was analysed and the auxetic behaviour was achieved by the differential shrinkage phenomenon of the weave structures.

Another approach is using auxetic yarns directly weaving into the fabric. In the early stage, auxetic woven fabric can be made using double helix yarns according to Wright, Burns [13] and Monika and Petra [29]. Their studies demonstrated the auxeticity and porosity of different fabric structure. The maximum negative Poisson's ratio of -0.1 was reported [13] and the 2/2 twill structure demonstrated the highest auxetic value compared with plain and 3/5 satin weaves [29]. In 2016, Hu's group created a new type of auxetic yarn with a 4-ply structure [30] and this type of yarns can be fabricated into new woven auxetic fabrics [31]. They pointed out the yarn arrangement, yarn properties, weft yarn type, weave structure and yarn helical structure have significant effect on the NPR of the fabric. Then, Du's group reported a self-curling and self-folding auxetic woven fabric experimentally with the maximum NPR of -0.585 [32, 33]. It was noted that such woven fabrics demonstrate a good auxeticity, low elastic deformation, high flexibility and breaking load. Moreover, Lolaki and Shanbeh [34] discussed fabric structural parameters such as thread density, weave design and wrap yarn count. They found that while fabric thread densities together with warp count influence the minimum fabric Poisson's ratio, auxetic behaviour of the samples is not dependent on weave design alone [34]. The maximum NPR value of the fabric can be achieved as -0.54 with a weft-backed satin design.

Based on the literature so far, the properties of the auxetic woven fabric still need to be investigated and the key factors for weaving the fabric need to be drawn systematically both in experimental and numerical ways. Thus, followed our research on auxetic yarns and woven fabrics [35, 36], the aim of this paper is to further investigate the auxeticity of the woven fabrics, and to provide principles for achieving the best NPR of the auxetic woven fabric by using experimental and numerical methods.

Table 1 Parameters of helical auxetic yarns (HAYs)

	HAY39	HAY34	HAY28	HAY20
Core Ply	Polyurethane	Polyurethane	Polyurethane	Polyurethane
Wrap Ply	Nylon 6,6	Nylon 6,6	Nylon 6,6	Nylon 6,6
Linear Density (Tex)	269	264	263	261
Wrapping Angle (°)	39	34	28	20

2 Materials and Methods

2.1 Manufacture of Helical Auxetic Yarns

To produce HAYs, a highly elastic polyurethane multifilament of 241.1 tex and a conventional nylon 6,6 of 16.5 tex were selected as the core and the wrap, respectively. A hollow spindle fancy-yarn machine with model GDM/MK2/M manufactured by Gemmill & Dunsmore Ltd was used for yarn production, where the core and the wrap can be twisted together with different parameters by changing the delivery speed and the twisting speed. Based on our previous research on HAYs [36], four types of yarns were used for further investigation, as listed in Table 1.

2.2 Fabrication of Auxetic Woven Fabrics

Such made auxetic yarns were selected for making woven fabrics. ARM AG CH-3507 BIGLEN semiautomatic hand weaving machine was used for fabric production, as shown in Fig. 1. In order to find the relationship between the yarns and fabrics, yarn HAY28 of 263.8 tex was selected as weft and Nylon 6,6 which is the binder of the helical auxetic yarn (HAY) was selected as warp for weaving a plain woven fabric. Based on our previous research on woven fabrics, the warp yarn sheet was given a 5% pre-stretch to meet the requirement for weaving and a constant basic warp tension level

Fig. 1 ARM AG CH-3507 BIGLEN semiautomatic hand weaving machine

Fig. 2 Pictures of DWF-Y28 and SWF-Y28

was maintained during the process [35]. Then a single weft fabric (SWF) and a double weft fabric (DWF) have been made with the same density, as shown in Fig. 2. For comparison purpose, SWF-Y39, SWF-Y34 and SWF-Y20 have been made as well using yarns HAY39, HAY34 and HAY20 as weft, respectively. The details of those fabrics are shown in Table 2.

2.3 FE modelling of Auxetic Woven Fabrics

To investigate the key factors of auxetic woven fabric under tension, finite element analysis was adopted using ABAQUS 2019 software. There are five main steps for the FE modelling. Firstly, Solidworks 2020 software is used for creating the fabric geometric model and the cross-section of the yarn within the fabric is assumed as an ellipse. In this study, the in phase arrangement of the auxetic yarns is created for the FE model, as shown in Fig. 3. Secondly, material properties are applied to the corresponding yarns. Based on the literatures of materials modelling [37, 38], all the yarns are set as isotropic materials. The warp yarn is set as an elastic property with 1850 MPa Young's modulus and 0.42 Poisson's ratio. The weft yarn, which is the HAY, is set as the same property of our previous report [36]. All the data is followed by the experiments above. Thirdly, a tensile loading is applied to one end of the weft yarns with the speed of 1 mm/s as a fixed constraint applied to the opposite end.

Table 2 Parameters of auxetic woven fabrics

	SWF-Y39	SWF-Y34	SWF-Y28	SWF-Y20	DWF-Y28
Warp	Nylon 6,6	Nylon 6,6	Nylon 6,6	Nylon 6,6	Nylon 6,6
Weft	HAY39	HAY34	HAY28	HAY20	HAY28
Weave structure	Single weft plain	Single weft plain	Single weft plain	Single weft plain	Double weft plain
Density	10×8 threads per cm	10×8 threads per cm	10×8 threads per cm	10×8 threads per cm	10×8 threads per cm

Fig. 3 FE model of the woven fabric

The interaction between the parts is set as ‘all with self’ along with a tie constraint between the warp yarns and the wrap plies. Then, in order to overcome the overlap problem of each part, the quadratic tetrahedral element shape with C3D10M model is adopted to the model. At last, the fabric model is submitted for running until the wrap ply of the weft yarn is broken.

To validate the model, SWF-Y28 was selected for comparison, as shown in Fig. 4. It was found that the two values had good accordance with each other. They exhibited the positive Poisson’s ratio first and subsequently decreased with the increasing strain. The highest value of the FE result was higher than that of the experimental result from strain 5% to 10% due to the sensitivity of the FE model. Then, the Poisson’s ratio of the FE model matched with the experimental result after 12.5% of strain within 15% of average percentage error. The maximum negative Poisson’s ratios between the experimental and the FE were shown at 17.5% of strain with the values of -1.09 and -1.3, respectively.

Fig. 4 Comparison between the experimental (SWF-Y28) and FE results

Fig. 5 Thickness of the fabric

3 Analysis on Fabric Auxeticity

Based on the findings of our research so far, the auxeticity of the woven fabric was not expected in dimensional changes but for the fabric cover [35]. In order to observe and maximize the thickness of the woven fabric, the auxetic yarns were selected for the weft direction only. Tensile tests were carried out using the INSTRON machine with the model number 2519–107 in the following analysis of experimental results. To observe the thickness of the fabric, a micro-focus UVC camera was set up on the side of the machine. According to the ASTM standard D1777-96, a blackboard was placed on the one side of the fabric for measuring the thickness of the fabric and keeping the fabric perpendicular to the micro-focus camera, as shown in Fig. 5. It is obvious that the fabric was thicker under tension. The thickness of the fabrics was tested three times for each sample during the tensile test with a gauge length of 50 mm and a crosshead speed of 60 mm/min.

Fig. 6 Poisson's ratio of plain (SWF), 2/2 warp rib (DWF) and 3/3 warp rib (TWF)

3.1 Weave structure

Three types of weave structures were created in ABAQUS 2019 software for analysis including plain, 2/2 warp rib and 3/3 warp rib, coded as SWF, DWF and TWF respectively. To investigate the effect of weave structure, other parameters of the fabric were kept the same including fabric density, mesh size, the warp and the weft yarn properties. Figure 6 shows the changes of Poisson's ratio of the three types of woven fabrics under tension. It can be seen that the trend of the fabric deformation is similar to the yarn deformation which was reported from our previous work [36]. In Fig. 6, TWF shows a higher auxetic effect compared with others because the fabric structure displays a longer float length and there are fewer weft yarns restricted by the warp yarns. During the stretching, the auxetic yarns within TWF have more freedom to be deformed. Thus, the weave structure with longer float length of the auxetic yarns results in higher auxetic behaviour.

3.2 Wrapping Angle of the HAY

Four types of auxetic yarns with different helical angles from 20° to 39° were selected for making woven fabrics, as shown in Table 2. The maximum NPRs of those fabrics were illustrated in Fig. 7, compared with the results of FE and the selected yarns. In Fig. 7, the maximum NPR of the yarn was overall higher than that of the corresponding fabric and the maximum value of the fabric was around 60% smaller than that of the corresponding yarn. This can be explained that the auxetic yarns were restricted by the warp yarns during the stretching and there existed interaction between the yarns. In addition, the auxetic behaviour of the fabric was increased from value -0.19 to -2.91 with the decreasing wrapping angles of the HAYs. The trends of the maximum NPR were similar between the yarns and the fabrics. Thus, the auxetic effect of the woven fabrics can be inherited from the auxetic yarns and the negative values were shown in fabric thickness rather than the warp direction. Combined the results of experiments and the FE, lower wrapping angles of the auxetic yarn result in higher auxetic behaviour of the fabric.

Fig. 7 Maximum NPR between auxetic fabrics and corresponding yarns with different angles

Fig. 8 Maximum NPR of the fabrics with different thickness of the weft yarn

3.3 Thickness of the HAY

Based on the validated fabric model above, the FE method can be used for analyzing the effect on thickness of the auxetic yarn which is the weft yarn. Five different thickness of the weft yarn was involved for the plain woven fabrics including 0.28 mm, 0.56 mm, 0.84 mm, 1.12 mm and 1.4 mm, respectively. Other parameters of the fabric were kept the same, such as the fabric density, mesh size, wrapping angle of the HAY and the weave structure. The thickness of the HAY within the fabric is smaller than that of the HAY because the cross section of the two plies in the HAY was deformed as a elliptic shape after weaving and the thickness of the fabric is mainly contributed by the vertical diameter of the HAY.

Figure 8 demonstrated the maximum NPR of the fabrics with different thickness of the auxetic yarn. It is obvious that the fabric shows a higher auxetic effect with decreasing thickness of the auxetic yarn because the contact area between the warp and weft yarns was larger when the fabric produced by thicker auxetic yarns. In addition, the thicker weft yarn showed less auxeticity because the core ply of the auxetic yarn was too soft and it was cut into the wrap ply under tension. Therefore, thicker auxetic yarn lead to lower auxetic effect of the fabric and this can provide a reference for researchers to select suitable yarn dimension for their fabric production.

3.4 Properties of the Warp Yarn

To investigate the effect of the warp yarn, other parameters of the auxetic woven fabric are kept constant, such as the weave structure, fabric density, wrapping angle of the HAY and the thickness of the HAY. Two types of effects were analysed for the warp yarn including the tensile modulus and the Poisson's ratio, as illustrated in Fig. 9.

First, for the changes of tensile modulus of the warp yarn, the Poisson's ratio was set as 0.42 corresponding to the yarn in experiments. Five tensile moduli of the warp were tried in the FE model including 1000 MPa, 1850 MPa, 3000 MPa, 4000 MPa and 5000 MPa, respectively. The results showed the auxetic effect was more obvious with the decreasing tensile modulus of the warp. Because when the warp yarn is softer, the

Fig. 9 Maximum NPR of the fabrics with different warp yarn

auxetic yarn will easily be deformed during the stretching and the restrictions between the yarns are smaller as well. Then, another property of the warp yarn is the Poisson's ratio. To further explore the variation of the warp, five different Poisson's ratios were created for the FE model from 0.3 to 0.48 with the same tensile modulus of 1850 MPa. It can be seen that the fabric showed the lowest auxetic effect when the Poisson's ratio reached 0.42. It reveals that the closer Poisson's ratio value between the warp and the wrap ply of the HAY, the lower auxeticity of the woven fabric. From the Poisson's ratio of 0.3 to 0.42, the maximum NPR of the fabric is decreased slowly, whereas from the value of 0.42 to 0.48, the gradient of the value is higher. This indicated that the fabric is more sensitive between the Poisson's ratio from 0.42 to 0.48 and the results also show the possibilities of the warp yarn selection for making auxetic woven fabrics.

4 Conclusions

This paper reported the development of woven fabrics made of helical auxetic yarns experimentally and numerically. The key factors on Poisson's ratio were discussed and the conclusions can be drawn as follows.

- (1) The weave structure can directly influence the auxeticity of the woven fabric and the structure obtained longer float length results in a higher auxetic effect of the fabric.
- (2) Lower wrapping angle of the HAY leads to higher auxetic behaviour of the fabric, however, the maximum value of the fabrics is around 60% smaller than that of the corresponding yarn.
- (3) Thicker weft yarn which is the HAY shows less auxeticity of the fabric.
- (4) Lower tensile modulus of the warp exhibits a higher auxetic effect. Closer Poisson's ratio value between the warp and the wrap ply of the HAY results in a lower NPR value of the fabric.

The auxeticity of the woven fabric suggests great potential for many technical applications such as filtration and impact protection. The reported findings in this paper can provide a reference for researchers to select the suitable parameters of the yarns for their fabric production. Moreover, there are still some works need to be done in the future such as the porosity and impact property of the auxetic woven fabric. These will be reported in our following paper.

Data Availability Statements The datasets analysed during the current study are not publicly available because they will be submitted to a PhD thesis of the first author, but are available from the corresponding author on reasonable request.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Wang, D., Naouar, N., Vidal-Salle, E., Boisse, P.: Longitudinal compression and Poisson ratio of fiber yarns in meso-scale finite element modeling of composite reinforcements. *Compos. B Eng.* **15**(141), 9–19 (2018)
2. Alderson, A.: A triumph of lateral thought. *Chem. Ind.* **17**, 384–391 (1999)
3. Evans, K.E., Alderson, A.: Auxetic materials: functional materials and structures from lateral thinking! *Adv. Mater.* **12**(9), 617–628 (2000)
4. Lakes, R.: Foam structures with a negative Poisson's ratio. *Science* **235**, 1038–1041 (1987)
5. Alderson, A., Alderson, K.L.: Auxetic materials. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering.* **221**(4), 565–575 (2007)
6. Alderson, A., Rasburn, J., Evans, K.E., Grima, J.N.: Auxetic polymeric filters display enhanced defouling and pressure compensation properties. *Membr. Technol.* **2001**(137), 6–8 (2001)
7. Scarpa, F., Bullough, W.A., Lumley, P.: Trends in acoustic properties of iron particle seeded auxetic polyurethane foam. *Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci.* **218**(2), 241–244 (2004)
8. Voigt, W.: Bestimmung der Elastizitätsconstanten für das chloresaurer Natron. *Ann. Phys.* **285**(8), 719–723 (1893)
9. Alderson, K.L., Alderson, A., Smart, G., Simkins, V.R., Davies, P.J.: Auxetic polypropylene fibres: Part 1-Manufacture and characterisation. *Plast., Rubber Compos.* **31**(8), 344–349 (2002)
10. Simkins, V.R., Alderson, A., Davies, P.J., Alderson, K.L.: Single fibre pullout tests on auxetic polymeric fibres. *J. Mater. Sci.* **40**(16), 4355–4364 (2005)
11. Alderson, K.L.: Progress in auxetic fibres and textiles. *Actual. Chim.* **1**:360:361 (2012)
12. Miller, W., Hook, P.B., Smith, C.W., Wang, X., Evans, K.E.: The manufacture and characterisation of a novel, low modulus, negative Poisson's ratio composite. *Compos. Sci. Technol.* **69**(5), 651–655 (2009)
13. Wright, J.R., Burns, M.K., James, E., Sloan, M.R., Evans, K.E.: On the design and characterisation of low-stiffness auxetic yarns and fabrics. *Text. Res. J.* **82**(7), 645–654 (2012)
14. Alderson, K., Alderson, A., Anand, S., Simkins, V., Nazare, S., Ravirala, N.: Auxetic warp knit textile structures. *physica status solidi (b)*. **249**(7):1322–9 (2012)
15. Hu, H., Wang, Z., Liu, S.: Development of auxetic fabrics using flat knitting technology. *Text. Res. J.* **81**(14), 1493–1502 (2011)
16. Glazzard, M., Breedon, P.: Weft-knitted auxetic textile design. *physica status solidi (b)*. **251**(2):267–72 (2014)
17. Subramani, P., Rana, S., Oliveira, D.V., Figueiro, R., Xavier, J.: Development of novel auxetic structures based on braided composites. *Mater. Des.* **1**(61), 286–295 (2014)

18. Shen, Y., Adanur, S.: Mechanical analysis of the auxetic behavior of novel braided tubular structures by the finite element method. *Text. Res. J.* **89**(23–24), 5187–5197 (2019)
19. Verma, P., Shofner, M.L., Lin, A., Wagner, K.B., Griffin, A.C.: Inducing out-of-plane auxetic behavior in needle-punched nonwovens. *physica status solidi (b)*. 252(7):1455–64 (2015)
20. Verma, P., Shofner, M.L., Lin, A., Wagner, K.B., Griffin, A.C.: Induction of auxetic response in needle-punched nonwovens: Effects of temperature, pressure, and time. *physica status solidi (b)*. 253(7):1270–8 (2016)
21. Dobnik Dubrovski, P., Novak, N., Borovinšek, M., Vesenjāk, M., Ren, Z.: In-plane behavior of auxetic non-woven fabric based on rotating square unit geometry under tensile load. *Polymers* **11**(6), 1040 (2019)
22. Hu, H., Zhang, M., Liu, Y.: *Auxetic textiles*: Woodhead Publishing, Sawston, Cambridge (2019)
23. Ali, M., Zeeshan, M., Qadir, M.B., Riaz, R., Ahmad, S., Nawab, Y., et al.: Development and mechanical characterization of weave design based 2d woven auxetic fabrics for protective textiles. *Fibers and Polymers*. **19**(11), 2431–2438 (2018)
24. Ali, M., Zeeshan, M., Ahmed, S., Qadir, B., Nawab, Y., Anjum, A.S., et al.: Development and comfort characterization of 2d-woven auxetic fabric for wearable and medical textile applications. *Cloth. Text. Res. J.* **36**(3), 199–214 (2018)
25. Hasan, K., Zulifqar, A., Hu, H.: Deformation behavior of auxetic woven fabric based on re-entrant hexagonal geometry in different tensile directions. *Text. Res. J.* **90**(3–4), 410–421 (2020)
26. Zulifqar, A., Hua, T., Hu, H.: Single- and Double-Layered Bistretch Auxetic Woven Fabrics Made of Nonauxetic Yarns Based on Foldable Geometries. *physica status solidi (b)*. 257(10):1900156 (2020)
27. Kamrul, H., Zulifqar, A., Yang, Y., Zhao, S., Zhang, M., Hu, H.: Geometrical analysis of auxetic woven fabrics based on foldable geometry. *Text. Res. J.* **9**, 00405175211008663 (2021)
28. Kamrul, H., Dong, W., Zulifqar, A., Zhao, S., Zhang, M., Hu, H.: Deformation behavior of auxetic woven fabric made of foldable geometry in different tensile directions. *Text. Res. J.* **91**(1–2), 87–99 (2021)
29. Monika, V., Petra, V.: Auxetic woven fabrics—pores’ parameters observation. *Journal of Donghua University (English Edition)*. (5):19 (2013)
30. Ge, Z., Hu, H., Liu, S.: A novel plied yarn structure with negative Poisson’s ratio. *The Journal of The Textile Institute*. **107**(5), 578–588 (2016)
31. Ng, W.S., Hu, H.: Woven Fabrics Made of Auxetic Plied Yarns. *Polymers* **10**(2), 226 (2018)
32. Liu, S., Pan, X., Zheng, D., Liu, G., Du, Z.: The manufacture and characterization of auxetic, self-curling, and self-folding woven fabrics by helical auxetic yarns. *J. Ind. Text.* **50**(1), 3–12 (2020)
33. Chen, J., Du, Z., Li, T.: Structural design and characterization of highly elastic woven fabric containing helical auxetic yarns. *Text. Res. J.* **90**(7–8), 809–823 (2020)
34. Lolaki, A., Shanbeh, M.: Variation of Poisson’s ratio of fabrics woven with helical composite auxetic weft yarns in relation to fabric structural parameters. *J. Ind. Text.* **50**(2), 149–169 (2020)
35. Gao, Y., Liu, S., Wu, M., Chen, X., Studd, R.: Manufacture and Evaluation of Auxetic Yarns and Woven Fabrics. *physica status solidi (b)*. 257(10):1900112 (2020). <https://doi.org/10.1002/pssb.201900112>
36. Gao, Y., Chen, X., Studd, R.: Experimental and numerical study of helical auxetic yarns. *Text. Res. J.* (2020). <https://doi.org/10.1177/0040517520977194>
37. Zeng, J., Cao, H., Hu, H.: Finite element simulation of an auxetic plied yarn structure. *Text. Res. J.* **89**(16), 3394–3400 (2019)
38. Wright, J.R., Sloan, M.R., Evans, K.E.: Tensile properties of helical auxetic structures: a numerical study. *Journal of Applied Physics*. 108(4):044905 (2010)