An Investigation of the Auxetic Behavior of Weft Knitted Fabrics

Chamika Madhurangi
Department of Textile and Apparel Engineering
University of Moratuwa
Sri Lanka
chamikam@uom.lk

Charuka Wijethunga
Department of Textile and Apparel Engineering
University of Moratuwa
Sri Lanka
171055u@uom.lk

Gamini Lanarolle
Department of Textile and Apparel Engineering
University of Moratuwa
Sri Lanka
wilath@uom.lk

Keywords— Auxetic textiles, Negative Poisson's Ratio, Weft knitted fabrics

I. INTRODUCTION

Auxetic materials exhibit extraordinary mechanical characteristics, displaying lateral expansion under axial tension and lateral contraction under axial compression – a behavior opposite to that of conventional materials. This unique property, attributed to their negative Poisson's ratio (NPR), opens exciting possibilities for enhanced performance in various applications, including lightweight structures with superior energy absorption, fracture resistance, shear resistance, acoustic absorption, and variable permeability [1].

The extensive range of potential applications spans diverse industries, including biomedical, aerospace, building and construction, smart textiles, and defense. For instance, biomedical devices like artificial blood vessels capitalize on the auxetic property to reduce the risk of rupture by widening when blood flows through [2]. In construction, auxetic materials are utilized as core materials in sandwich panels to achieve high structural rigidity with minimal weight [3]. Smart textiles made from auxetic fibers and yarns offer increased dent and fracture resistance, as well as enhanced energy absorption for protective gear in sports and defense applications [4].

The development of auxetic fabrics has become increasingly feasible due to advancements in fabric manufacturing technologies. Weft knitting, known for its process flexibility and structural versatility, emerges as an ideal technique to create auxetic fabrics.

In this project, we focus on creating auxetic weft knitted structures using non-auxetic yarns and exploring their mechanical behavior and properties. Drawing inspiration from auxetic metamaterial structures, we designed four distinct auxetic fabric structures, namely foldable zigzag, rotating square, missing rib, and double arrowhead structures. Among these, the foldable zig-zag structure exhibited the most promising NPR results, leading to further analysis by varying the repeat unit cell. Given the significant influence of loop length on auxetic properties [5], we investigate fabrics with the same zig-zag structure but different loop lengths.

Through achieving these objectives, this study seeks to contribute to a comprehensive understanding of auxetic weft knitted structures and their potential applications across industries.

II. MATERIALS AND METHODS

A. Material Selection

Acrylic yarn with 72 tex was chosen for knitting all fabric samples. While yarn type may influence NPR, acrylic yarn was selected due to its availability and its potential for achieving an optimum negative Poisson ratio through changing structural parameters.

B. Machinery Selection

The knit samples were produced using a Shima Seiki Flatbed Knitting Machine (SES 122s) with gauge 10, allowing for quick and precise sample production. The SDS-ONE Knit Paint software was used for programming each textile prototype.

C. Auxetic Structure Development

Inspired by metamaterials, the project involved developing and analyzing several auxetic weft-knitted structures: foldable zig-zag structures, missing rib structures, rotating square structures, and double arrowhead structures.

D. Testing for Auxetic Effect

To determine the Poisson's ratio, a unique clamping method was employed using two aluminum rods connected to the fabric edges. This method minimized movement restrictions caused by clamping. The deformation of fabrics under load was recorded using a digital camera, and Poisson's ratio was calculated from the strain measurements.

$$\varepsilon_x = \frac{X_k - X_0}{X_0} \qquad (1)$$

$$\varepsilon_y = \frac{Y_k - Y_0}{Y_0} \qquad (2)$$

Using the strain values (1) and (2), the Poisson's ratio was calculated. The relationship between strain values and Poisson's ratio is (3).

$$\upsilon_{yx} = -\frac{s_x}{s_y} \qquad (3)$$

III. RESULTS AND DISCUSSION

The study focused on exploring the auxetic properties of various weft-knitted structures, including foldable zigzag, missing rib, rotating square, and double arrowhead. Image analysis data was collected and used to calculate Poisson's ratio and strain in the course direction. The results showed some variations and inconsistencies due to the fabric's three-dimensional nature, which caused the curves to appear bumpy.

Knit loop instability played a crucial role in generating auxetic behavior in the fabrics. The inherent curly configuration of knit loops led to structural disequilibrium and the formation of 3D structures upon relaxation. When a force was applied, these structures unfolded and increased in both course and wale directions, exhibiting an auxetic effect.

A. Foldable Zigzag Structures

Foldable Zigzag structures were divided into three categories according to the number of courses and wales, (1) courses = wales, (2) courses < wales, and (3) courses > wales. Knitted samples are shown in Fig. 1.

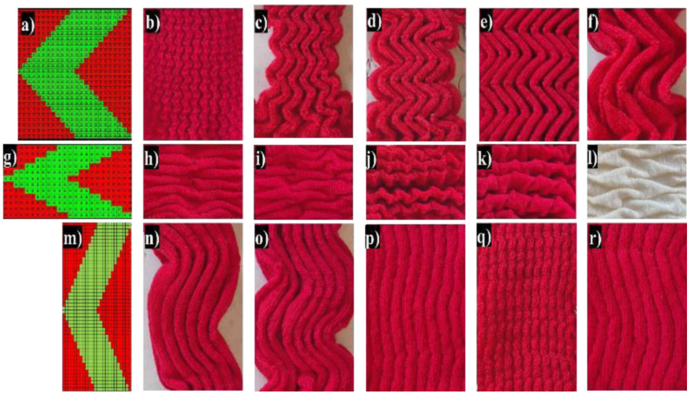

Fig. 1. Fig.4. a) Repeat unit of 24x24 pattern b) 6x6 c) 12x12 d) 18x18 e) 24x24 f) 36x36 g) Repeat unit of 12x24 h) 12x48 i) 12x36 j) 12x24 k) 18x36 l) 24x48 m) Repeat unit of 48x24 n) 48x24 o) 36x18 p) 36x12 q) 18x6 r) 48x12

Influence of the repeat unit size was examined, and it was found that the best auxetic behavior was achieved when the number of courses equaled the number of wales. The 24x24 fabric structure demonstrated the highest negative Poisson's ratio value of -0.74. This result aligns with theoretical expectations in the sense that a balanced configuration of courses and wales tends to promote higher auxetic effects. Smaller repeat unit sizes tended to be more stable, while larger sizes became less stable and lost their folded shape. Fig. 2 shows the NPR behavior of samples, 6x6, 12x12, 18x18, 24x24 and 36x36 where number of courses equals to the wales.

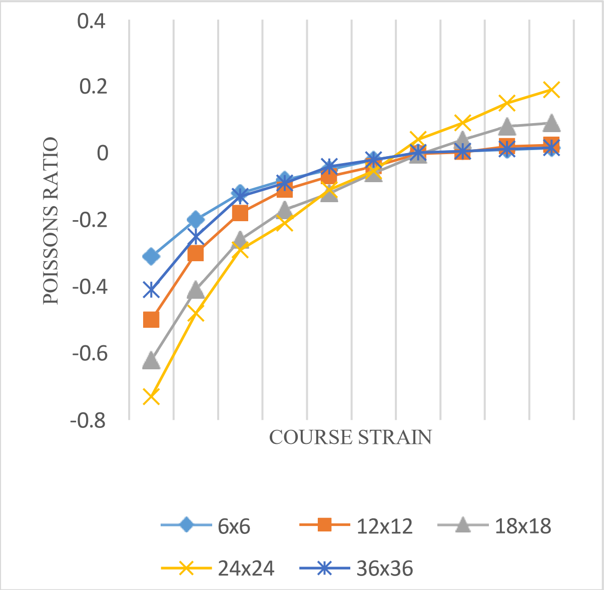

Fig. 2. NPR values of foldable zigzag fabrics (courses=wales)

The influence of stitch/loop length on auxetic behavior was also investigated. The lowest loop length showed the best auxetic effect. Lower loop lengths led to increased fabric shrinkage, contributing to a more significant bending and curling effect, resulting in higher auxetic properties.

B. Missing Rib Structure

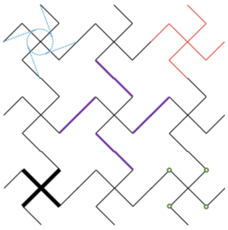

Fig 3: Swastika/ missing rib structure

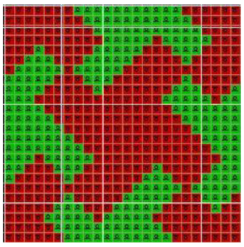

Fig 4: Repeat unit of missing rib structure

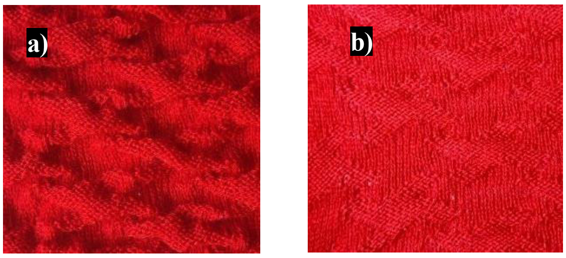

Fig.5: Swasthika knitted fabric a) relaxed fabric b) stretched fabric

The missing rib model, also known as the tilted-swasthika model which is shown in Fig.3, is a well-known auxetic metamaterial structure proposed by Smith et al.[6]. In its rigid form, the structure consists of bolded ribs that can be rotated, with the middle connected to each other. During contraction, each unit rotates in one direction, and during expansion, it reverses. The repeat unit used to knit the fabric is shown in Fig.4. In the knitted fabric, the rotation is not as prominent as in the rigid structure (Fig.5), but a slight rotation can be observed at the edges of the swasthika structure. When a force is applied, the fabric exhibits a slight rotation and expands in the lateral direction, demonstrating an auxetic effect.

C. Rotating Square Structure

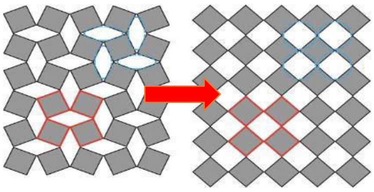

Fig 6: Rotating Square structure

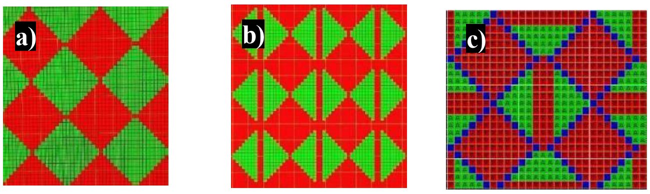

Fig. 7: Patterns developed to mimic rotating square structure (Green colour: Knit on back bed, Red colour: knit on front bed, blue color: tuck stitches)

The rotating square structure as shown as Fig. 6 is a known auxetic metamaterial that deforms based on its geometric arrangement. In its rigid form, the structure consists of linked corners of square units, and when stretched, the angle between the units changes, causing the structure to rotate and expand in both directions. To create a knit structure with similar behavior, three patterns were developed as shown in Fig.7. The first pattern used face and reverse loops to create squares of front and back loops alternately, but it showed a low auxetic effect. The second pattern added a separate line of back stitches to divide the squares, leading to a slightly improved auxetic effect. In the third pattern, tuck stitches were added to better mimic the rigid structure, but the fabric sample did not expand as expected upon stretching, possibly due to insufficient force at the fabric edges. The fabric behaviors are shown in Fig.8.

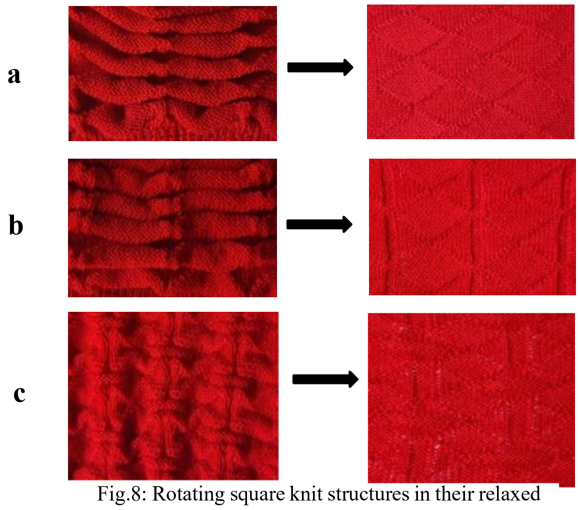

Fig.8: Rotating square knit structures in their relaxed and stretched state

D. *Double Arrowhead Structure*

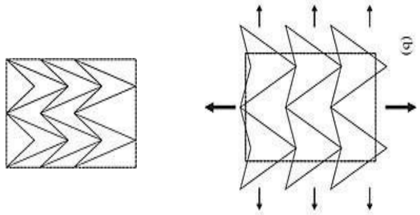

Fig.9: Expansion of double arrowhead structure

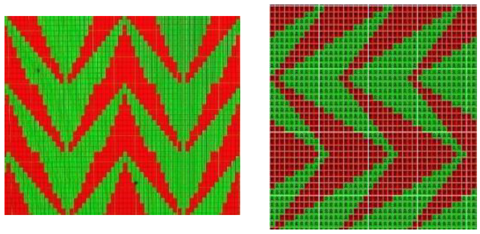

Fig.10: Knit programs to create double arrowhead structures for two directions

The double arrowhead model, identified as an auxetic metamaterial by Larsen et al. [7], consists of two intersecting double heads at their axis of symmetry. When a force is applied in the course direction, the structure expands laterally (Fig.9). Two structures were developed using this concept, but with different orientations of the arrowheads, differing by 90 degrees as shown in Fig. 10. Although both structures had the same repeat unit, the fabric where the arrowhead pointed towards the course direction showed a significantly higher NPR compared to the fabric where the arrowhead was pointed downwards. This observation indicates that the direction of the pattern repeat unit also plays a role in determining the auxetic effect. The behavior of the fabric is shown in Fig. 11.

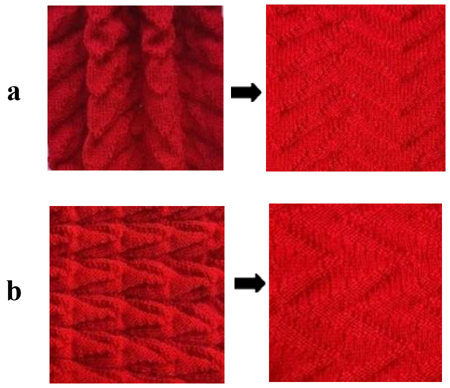

Figure 11: Knitted double arrowhead structures in their relaxed and stretched states

IV. CONCLUSION

In conclusion, this research aimed to explore the auxetic behavior of weft knitted fabrics. Through a comprehensive literature review, valuable insights into auxetic structures were gathered. Several metamaterial-inspired structures were developed, including the missing rib structure, rotating square structure, double arrowhead structure, and foldable zig-zag structure. Among these, the foldable zig-zag structure exhibited the most significant auxetic effect. Furthermore, the orientation of fabric patterns has a notable impact on both auxetic behavior and mechanical response. Future research directions include exploring diverse material combinations, investigating dynamic fabric behavior, developing multi-scale models, functionalizing fabrics for specific applications, and optimizing auxetic fabrics for industry-specific needs, promising innovative developments in materials science and engineering.

V. REFERENCES

[1] V. H. Carneiro, J. Meireles, and H. Puga, “Auxetic materials — A review,” Mater. Sci.-Pol., pp. 561–571, 2013, doi: 10.2478/s13536-013-0140-6.

[2] L. Song, M. F. Ahmed, Y. Li, C. Zeng, and Y. Li, "Vascular differentiation from pluripotent stem cells in 3-D auxetic scaffolds," *J. Tissue Eng. Regen. Med.*, vol. 12, no. 7, pp. 1679–1689, Jul. 2018, doi: 10.1002/term.2695.

[3] D. Qing-tian and Z. Yang, "Wave Propagation in Sandwich Panel with Auxetic Core," *J. Solid Mech.*, vol. 2, Jan. 2010.

[4] F. Steffens, S. Rana, and R. Fangueiro, "Development of novel auxetic textile structures using high performance fibres," *Mater. Des.*, vol. 106, May 2016, doi: 10.1016/j.matdes.2016.05.063.

[5] Y. Sun, W. Xu, W. Wei, P. Ma, and F. Xia, "Stab-resistance of auxetic weft-knitted fabric with Kevlar fibers at quasi-static loading," *J. Ind. Text.*, vol. 50, p. 152808371986504, Jul. 2019, doi: 10.1177/1528083719865044.

[6] C. W. Smith, J. N. Grima, and K. E. Evans, "A novel mechanism for generating auxetic behaviour in reticulated foams: missing rib foam model," Acta Mater., vol. 48, no. 17, pp. 4349–4356, Nov. 2000, doi: 10.1016/S1359-6454(00)00269-X.

[7] U. D. Larsen, O. Signund, and S. Bouwsta, "Design and fabrication of compliant micromechanisms and structures with negative Poisson's ratio," J. Microelectromechanical Syst., vol. 6, no. 2, pp. 99–106, Jun. 1997, doi: 10.1109/84.5857