Tensile and bending properties of flexible auxetic re-entrant honeycomb structures made by 3D printing

DOI: 10.35530/IT.071.02.1565

DU ZHAOQUN
XU QIAOLI
GU LONGXIN
ZHENG DONGMING
WANG QICAI

ABSTRACT – REZUMAT

Tensile and bending properties of flexible auxetic re-entrant honeycomb structures made by 3D printing

The main content dealt with in the paper was to present a flexible auxetic re-entrant honeycomb fabric, which was made of a formulated thermoplastic polyurethane material PolyFlex with super elastic properties by 3D printing technology. The auxetic fabric shows perpendicular expansion under tension and is flexible. So, its special property makes auxetic fabric have great potential in future functional materials. Wherein, the honeycomb cell angle is a key factor affecting Poisson's ratio of fabric. In this paper, flexible re-entrant honeycomb structures with different cell angle are manufactured using 3D printing technology. The shape change under tension of two directions were investigated. The re-entrant honeycomb structures presented negative Poisson's ratio immediately when stretched. The shape change consisted of three stages in X_1-direction, the same as that in X_2-direction. A noticeable discovery was that the shape change in X_1-direction posed an out-plane change after the first shape change stage, while the shape change in X_2-direction always remained in-plane in the whole tension process. The tensile modulus tested was consistent with the tendency of theoretical analysis of previous work. The bending rigidities were tested and similar to fabrics of poplin and denim. The results indicate that the auxetic fabric is suitable for special clothing.

Keywords: *flexible auxetic honeycombs, 3D printing, negative Poisson's ratio, shape change, bending rigidity*

Rezistenţă la rupere și rigiditatea la încovoiere ale structurilor auxetice flexibile de tip fagure, realizate prin imprimare 3D

Lucrarea analizează, în principal, materialul auxetic flexibil de tip fagure, realizat din poliuretan termoplastic tip PolyFlex cu proprietăți supraelastice, obținut prin tehnologia de imprimare 3D. Materialul auxetic prezintă expansiune pe direcție perpendiculară sub tensiune și este flexibil. Astfel, materialul auxetic prezintă un potențial mare pentru produsele funcționale viitoare. În acest caz, unghiul celulelor de tip fagure este un factor cheie care influențează raportul lui Poisson. În această lucrare, sunt prezentate structuri flexibile de tip fagure cu unghiuri diferite ale celulelor, realizate utilizând tehnologia de imprimare 3D. S-a analizat modificarea formei sub tensiune pe două direcții. Structurile de reumplere de tip fagure au prezentat un raport negativ al lui Poisson imediat după întindere. Modificarea formei a constat în trei etape pe direcția X_1 și asemănător pe direcția X_2. O descoperire vizibilă a fost aceea că modificarea formei în direcția X_1 s-a realizat înafara planului, după prima etapă, în timp ce în direcția X_2 a rămas întotdeauna în planul întregului proces de tensiune. Modulul de rezistență la rupere testat a fost în concordanță cu tendința identificată în analiza teoretică din studiile anterioare. Rigiditățile la încovoiere au fost testate și au fost similare cu cele ale țesăturilor din poplin și denim. Rezultatele au indicat faptul că materialul auxetic este potrivit pentru realizarea îmbrăcămintei speciale.

Cuvinte-cheie: *structuri auxetice flexibile de tip fagure, imprimare 3D, raportul lui Poisson negativ, modificarea formei, rigiditatea la încovoiere*

INTRODUCTION

When a sample of material is stretched, it is naturally expected that a contraction in the direction perpendicular to the stretching direction will occur. Poisson's ratio is the quantity defining this fundamental material feature. On the contrary, a material with a negative Poisson's ratio expands in all directions when pulled, leading to an increase in its volume. Evans [1] was the first to make such materials as auxetic materials with a negative Poisson's ratio. Beside the elementary scientific importance of imparting such a fundamental property, a negative Poisson's ratio can attribute a material with many exceptional benefits [2], such as increased stiffness [3], increased indentation resistance [4] and an ability to form synclastic doubly curved surfaces [5–6].

In recent years, the use of textile technology to fabricate auxetic materials has attracted more and more attention. It is reflected in the extent of research work exploring the auxetic potential of various textile structures and subsequent increase in the number of research papers [7]. Particularly, auxetic yarns have been studied thoroughly. Du manufactured helical auxetic yarns and analyzed the auxetic effect using finite element analysis based on ABAQUS software and theoretical formula [8]. Hu created a new method to manufacture auxetic yarns which had more stable structures, and manufactured a novel auxetic textile composites [9, 10] according to the re-entrant honeycomb structures. Ugbolue produced knit structures made of conventional yarns by using chain and filling yarn inlays. They combined the principles of geometry, fabric structural characteristics and conventional elastic yarn to engineer hexagonal knit structures with auxetic effect [11]. Recently, a range of auxetic knitted fabric had been produced by using weft flat knitting technology [12–13]. Based on rotating units, auxetic fabric was produced [14]. Verma reported that it was possible to induce out-of-plane auxetic behaviour in needle-punched nonwovens [15]. These auxetic textiles have great potential to be used in many areas like biomedical field, filters, piezoelectric sensors and actuators, medical field, seat belts and safety harness in automobiles, ballistic protection, reinforcement composites. Except the traditional textile technology, such as weaving [4], knitting [14, 16–18] and non-woven [19], 3D printing is a direct and effective method to fabricate complex auxetic structural designs. Meanwhile, auxetic materials can be used in smart systems and enforce composite materials [20–21].

Combinations of 3D printing with typical auxetic structures would also change the way of auxetic textiles manufacturing [22]. Actually, for the tension property of re-entrant honeycombs, the traditional auxetic structures of rigid materials had been investigated by scientists in the area of mechanical engineering [23–24]. All these articles dealt with the shape change under little strain and gave equations of Poisson's ratio and Yong's modulus. The Poisson' ratios of honeycombs were supposed to be determined by the geometry of their unit cells only. However, the shape change of flexible materials was a complex process, which call for intensive investigation in order to establish a proper understanding.

Therefore, the paper aims to produce a flexible auxetic re-entrant honeycomb fabric made of a formulated thermoplastic polyurethane material PolyFlex with super elastic properties by 3D printing technology, and to discover the tensile deformation of the auxetic fabric under two directions so as to analyze effect of cell angle on Poisson's ratio. In addition, the shape changes under tension of two directions were investigated in these flexible re-entrant cell honeycombs structures.

EXPERIMENTAL DETAILS

Design of geometric unit cell parameters of re-entrant honeycomb structures

Re-entrant honeycomb unit cell is characterized by four indices, i.e., cell wall of length h and l, thickness t and internal cell angle θ as seen in figure 1. When the length h and l are fixed, the internal cell angle has significant effect on Poisson ratio. So, five typical internal cell angles θ are chosen as –45°, –40°, –35°, –30°, –25°, and the h, l and t are 10, 5 and 0.6 mm, respectively. The samples of tensile experiment were made in 5 unit cells´5 unit cells and two plain areas were added to the structures in order to measure conveniently. In addition, tensile test on two directions (X_1 and X_2 in figure 1) were carried out and illustrations of such sample tested in the two directions are shown in figure 2. For bending rigidity measurement, the samples are printed in 50 mm × 200 mm.

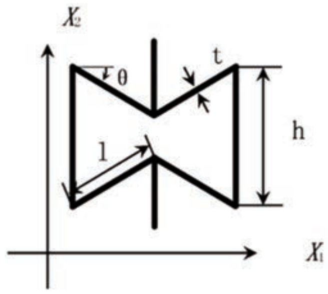


Fig. 1. Unit cell of a model of re-entrant honeycomb structures

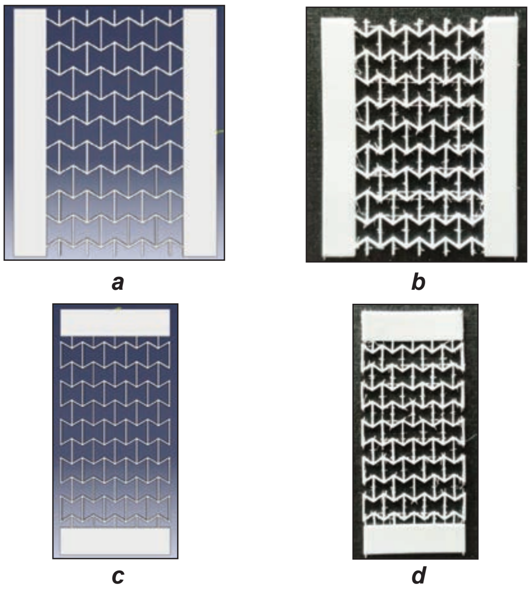


Fig. 2. A typical re-entrant structural model and sample: *a* – model for tensile use in X_1 direction; *b* – sample for tensile use in X_1 direction; *c* – model for tensile use in X_2 direction; *d* – sample for tensile use in X_2 direction

3D Printing process

Twenty specimens were manufactured by Raise3D N2 system based on fused deposition modeling technique (FDM). The material used in this work was PolyFlex, which was a formulated thermoplastic polyurethane material with super elastic properties. The Young's Modulus of PolyFlex is 58.57 MPa according to ASTM D638.

The manufacturing principle was based on a multi-jet modelling technology, where a special printing head covered the whole working area of 305 mm × 305 mm × 305 mm and built up the model by adding individual layers of the produced geometry.

A SolidWorks parametric modeler was used to design the sample geometry, and then it was exported to the STL format for the 3D printing. The final samples were produced with a layer thickness of 0.1 mm and the total depth of each sample is 1.5 mm.

Measurement method

Tensile tests were implemented by YG026MB Fabric Strength Tester. The tensile speed was set to 200 mm/s. The Young's modulus *E* was measured from the slope of the linear elasticity section on load-deflexion curve (the strain from 0.1% to 0.3%). In order to analyse the cell size change, a microfocus camera was employed to record the tensile deformation during the test until the out-of-plane change reached its maximum in the X_1-directional testing or the transverse width became smaller than 2/3 of its original width in the X_2-directional testing, which the plane formed by X_1 and X_2 directions. Therefore, out-of-plane shape change means change occurs on the planes perpendicular to the plane formed by X_1 and X_2 directions. Image process software DIGIMIZER was adopted to calculate the shape change in perpendicular direction, and the perpendicular strains and longitude strains were measured to calculate the Poisson's ratio of the honeycomb structures. Poisson's Ratio υ is defined as the minus of specific value between transverse strain and longitudinal strain in elastic loading.

Bending properties were implemented by FAST-2 Fabric bending tester and the bending meter measures two bending properties of a sample, namely the fabric bending length is related to the ability of a material to drape. The fabric bending rigidity relates to the quality of stiffness when a fabric is handled. The bending rigidity is particularly crucial in the tailoring of lightweight fabrics as a very flexible fabric (low bending rigidity) may cause seam puckering, while a high bending rigidity fabric can be more manageable in sewing and so produce a flat seam. The bending length (BL) is displayed automatically [25–26].

RESULTS AND DISCUSSIONS

The strain change in both directions

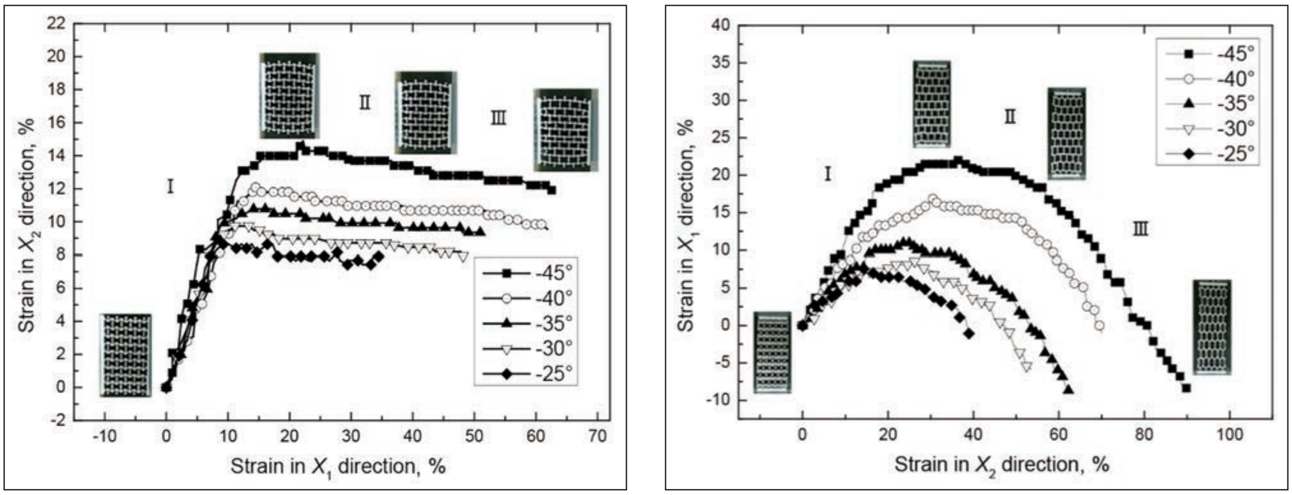
It can be seen from figure 3, *a* and *b* that the shape change of 3D printing honeycombs is distinct and they can show expanding in transverse direction at the same time of tension of longitudinal direction. The shape change process in X_1-direction consisted of three stages. In the first stage in figure 3, *a*, shape change remained in-plane and the cell wall length l was almost parallel to the X_1-direction before reaching the highest strain for every sample. The out-plane shape change occurred in stage two, while out-plane shape change strain started decrease in stage three and the whole structure was broken in the edge.

The shape change in X_2-direction also included three stages, but it remained in-plane during the whole process. The first stage mainly consisted of the rotation of cell wall l and the perpendicular width reached its maximum and cell wall l was parallel to X_1-direction. After that, the perpendicular width remained wider than the original width, but it began to decrease at the second stage. It can see from figure 3, *b* that the re-entrant honeycomb structures would become an out-entrant honeycomb structures at the end of the second stage. The last stage of shape change in X_2-direction was simple, like a positive Poisson's ratio material.

At the edge of structures broken, the extending in X_2-direction was far bigger than that in X_1-direction. The perpendicular increasing under the tension in X_1-direction was much more steady, while the perpendicular increasing in X_2-direction increased with the increase of longitudinal increasing, and then decreased until smaller than the original width. There was also a distinct phenomenon that the tension in X_1-direction leading to an out-plane expanding, but the shape change in X_2-direction always remained in-plane. We could discuss the out-plane shape change in these serials of paper.

Typical Poisson's ratio-strain curve

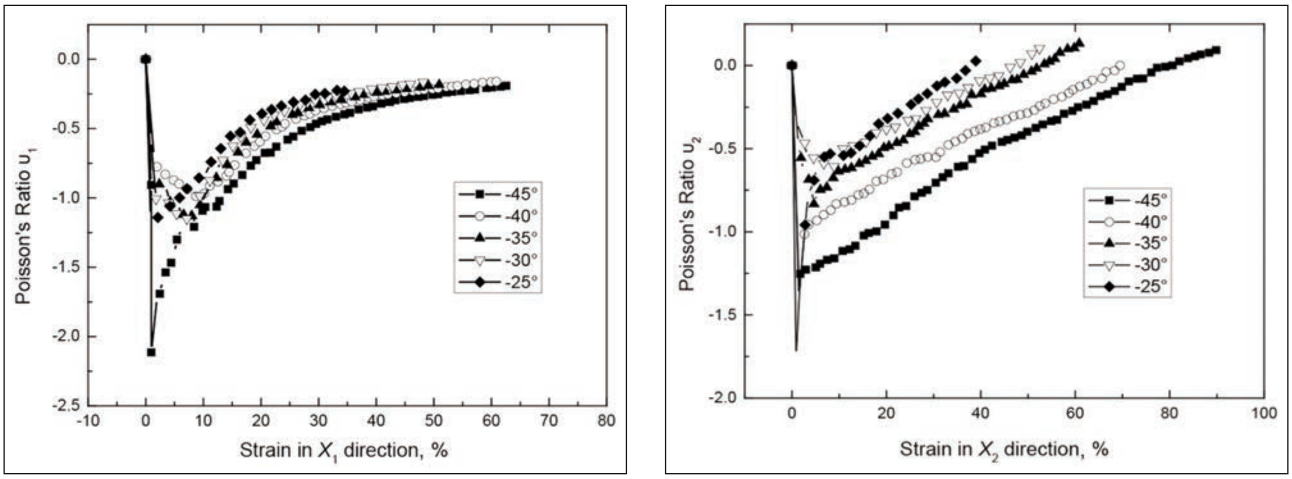
According to figure 4, *a* and *b*, the change of Poisson's ratio varies with the change of strain in different longitudinal directions. The Poisson's ratio had a closer relationship with the angle θ. Obviously dif-



a

b

Fig. 3. The transverse strain vs. longitudinal strain in X_1 and X_2 directions: *a* – tensile loading in X_1-direction; *b* – tensile loading in X_2-direction



a *b*

Fig. 4. The Poisson's ratio vs. longitudinal strain under tension for different cell angle: *a* – tensile loading in X_1 direction; *b* – tensile loading in X_2 direction

ferent samples had the smallest Poisson's ratio in different longitudinal strain, less than 10% in X_1-direction and less than 5% in X_2-direction. Meanwhile, the material properties were more important than the geometry parameters in the big strain area because the v change tendencies are similar in all angles after the small strain change zones. And the re-entrant angle plays a more significant role in X_2-direction than in X_1-direction, which in same tensile strain, 20%, the standard deviation of Poisson's ratio in X_1-direction is 0.12, while 0.25 in X_2-direction.

In addition, there was a discovery that the Poisson's ratio was smaller in small angle θ under same strain within the second stage. At the initial stage, both shape change process in experiments were not very clear and experimental error was a little large. On the other hand, the most significant difference between figure 4, *a* and *b* was the line tendency. In figure 4, *a*, the line changed in a shape of exponential form, while in figure 4, *b*, the line was almost linear.

Young's modulus

It can be seen from figure 5 that the angle θ of the 3D printed flexible auxetic structures also had a significant effect on the Young's Modulus. The E_1 in direction of X_1 increased remarkably with the increase of angle θ, while the E_2 in direction of X_2 was quite different, decreased slowly with the increase of angle θ. They were almost equal in about angle 44°. The trend of *E* change was consistent with the theoretical result of flexure model [24, 27].

Bending rigidity

It can be seen from table 1 that the bending rigidities and weight per square meter were given. As the cell angle increased, weight per square meter decreased dramatically. The bending rigidities were larger than the normal fabrics and were similar to the fabrics of poplin and denim [27–29]. The curves of bending rigidities were shown in figure 6.

Table 1

WEIGHT PER SQUARE METER AND BENDING RIGIDITY OF SAMPLES

Angle θ (°)	Weight per square meter (g/m^2)	B-X_1 direction (μN·m)	B-X_2 direction (μN·m)
–45°	511.6	4869.70	4869.70
–40°	446.9	5522.16	4253.47
–35°	398.5	6101.58	3792.92
–30°	352.5	4989.07	3669.31
–25°	317.2	4732.15	3205.74

It is obvious from figure 6 that the bending rigidity in X_1 direction reached its top when the angle was –35, while it remained decrease constantly in X_2 direction. It may be attributed to different parts of the re-entrant structures. For the bending in X_1 direction, the inclined edges with length *l* loaded more and the shape change process was complicate. On the other

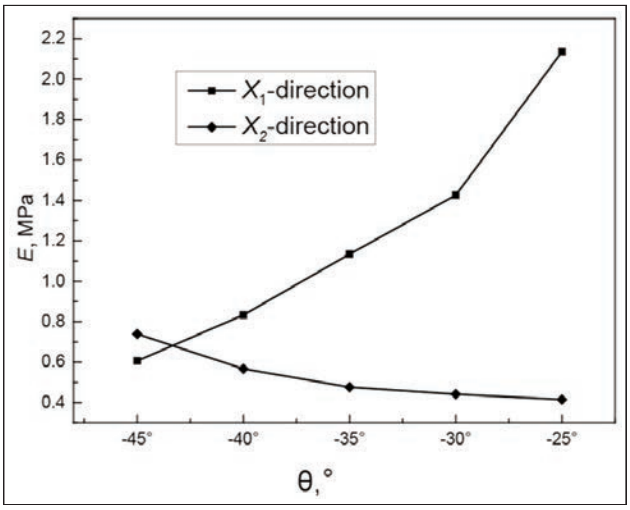


Fig. 5. The Yong's module of different samples

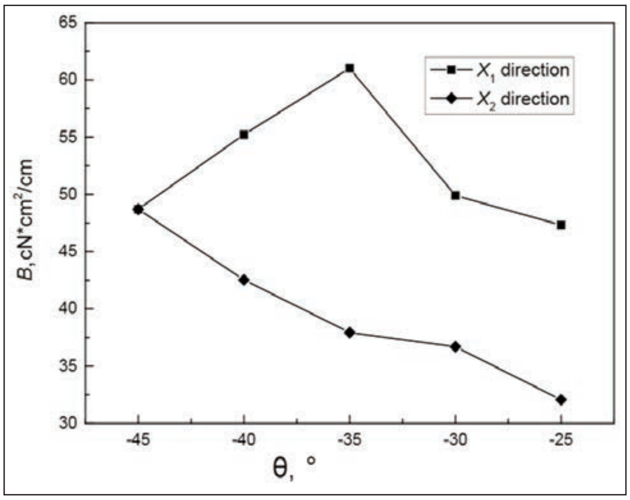


Fig. 6. Bending rigidities of samples

hand, the bending behaviour in X_2 direction was caused mainly by the bending of cell walls with length *h*, and it was more like a beam bending.

When the comparisons were made between figure 5 and figure 6, there was a discovery that in the angle of –45°, the bending rigidities in two directions were same, and the Young's modulus were also close for the two directions.

CONCLUSION

The samples of flexible re-entrant honeycomb structures were manufactured by 3D printing technology. Through using microfocus camera and software DIGIMIZER, the process of shape change was investigated. They both express negative Poisson's ratio. Meanwhile, the honeycomb structures can show negative Poisson's ratio at the same time of loading. The shape change process was different in two tension directions. When the load was possessed in X_1-direction, the honeycomb structures would expand and showed out-plane negative Poisson's ratio, while if the load was possessed in X_2-direction, the honeycomb structures would perpendicularly expand and then contract, meanwhile, the shape change process remained in-plane. The Young's module increased with the increase of angle in X_1-direction; while decreased with the increase of angle in X_2-direction. This was consistent with theoretical analysis in former papers. The bending rigidity of 3D printed fabrics was similar to the fabrics of poplin and denim. Finite element analysis of the structures will be done in next paper.

ACKNOWLEDGEMENT

This work is jointly supported by Jiangxi Provincial Bureau for Quality and Technical Supervision (GZJKY201807), Jiangxi Provincial Administration for Market Regulation (GSJK201909) and "The Fundamental Research Funds for the Central Universities (CUSF-DH-D-2017021)". One of the authors (Qiaoli Xu) gratefully acknowledges the scholarship from the China Scholarship Council (No. 201706630070).

REFERENCES

[1] Evans, K.E., Alderson, A., Christian, F.R., *Auxetic two-dimensional polymer networks. An example of tailoring geometry for specific mechanical properties*, In: Journal of the Chemical Society, Faraday Transactions, 1995, 91, 16, 2671–2680

[2] Umakiran, T., Kumar, A.A., *Auxetic textile and its applications*, In: Man-Made Textiles in India, 2009

[3] Evans, K.E., Alderson, K.L., *Auxetic materials: the positive side of being negative*, In: Engineering Science and Education Journal, 2000, 9, 4, 148–154

[4] Alderson, A., *A triumph of lateral thought*, In: Chemistry and Industry (London), 1999, 10

[5] Yang Z., Deng, Q., *Merchanical property and application of materials and structures with negative Poisson's Ratio*, In: Advances in Mechanics, 2011, 3, 335–350

[6] Evans, K., *Tailoring the negative Poisson ratio*, 1990

[7] Rant, D., Rijavec, T., Pavko-Čuden, A., *Auxetic textiles,* In: Acta Chimica Slovenica, 2013, 60, 4, 715-723

[8] Du, Z., et al., *Study on negative Poisson's ratio of auxetic yarn under tension: Part 1 – Theoretical analysis*, In: Textile Research Journal, 2015, 85, 5, 487–498

[9] Ge, Z., Hu, H., Liu, S., *A novel plied yarn structure with negative Poisson's ratio*, In: Journal of the Textile Institute, 2015, 1–11

[10] Ge, Z.Y., Hu, H, *Design and compression deformation analysis of an innovational structure with auxetic effect*, In: Applied Mechanics and Materials, 2013, 99-103

[11] Ugbolue, S.C., et al., *Auxetic fabric structures and related fabrication methods*, US, 2014

[12] Liu, Y., et al., *Negative poisson's ratio weft-knitted fabrics*, In: Textile Research Journal, 2010, 80, 9, 856–863

[13] Liu, Y., Hu, H., *A review on auxetic structures and polymeric materials*, In: Scientific Research and Essays, 2010, 5, 10, 1052-1063

[14] Hu, H., Wang, Z., Liu, S., *Development of auxetic fabrics using flat knitting technology*, In: Textile Research Journal, 2011, 81, 14, 1493–1502

[15] Verma, P., et al., *Inducing out-of-plane auxetic behavior in needle-punched nonwovens*, In: Physica Status Solidi (B) Basic Research, 2015, 252, 7, 1455–1464

[16] Ma, P., Chang, Y., Jiang, G., *Design and fabrication of auxetic warp-knitted structures with a rotational hexagonal loop*, In: Textile Research Journal, 2015, 86, 20, 2151–2157

[17] Steffens, F., Rana, S., Fangueiro, R., *Development of novel auxetic textile structures using high performance fibres,* In: Materials & Design, 2016, 106, 81–89

[18] Ugbolue, S.C., et al., *The Formation and Performance of Auxetic Textiles*, In: Journal of the Textile Institute, 2000, 102, 5, 424–433

[19] Verma, P., et al., *Induction of auxetic response in needle-punched nonwovens: Effects of temperature, pressure, and time*, In: Physica Status Solidi, 2016

[20] Scarpa, F., et al., *Auxetics in smart systems and structures 2015*, In: Smart Materials and Structures, 2016, 25, 5

[21] Zorzetto, L., Ruffoni, D., *Re-entrant inclusions in cellular solids: From defects to reinforcements*, In: Composite Structures, 2017, 176, 195–204

[22] Grimmelsmann, N., Meissner, H., Ehrmann, A., *3D printed auxetic forms on knitted fabrics for adjustable permeability and mechanical properties*, In: IOP Conference Series: Materials Science and Engineering, 2016

[23] Gibson, L.J., et al., *The Mechanics of Two-Dimensional Cellular Materials*, In: Proceedings of the Royal Society A, 1982, 382, 1782, 25–42

[24] Masters, I.G., Evans K.E., *Models for the elastic deformation of honeycombs,* In: Composite Structures, 1996, 35, 4, 403–422

[25] Minazio, P.G., *FAST – Fabric Assurance by Simple Testing*, In: International Journal of Clothing Science & Technology, 1995, 7, 2/3, 43-48

[26] Barndt H., et al., *The Use of KES and Fast Instruments*, In: International Journal of Clothing Science & Technology, 1990, 2, 3, 34–39

[27] Liu, C., Han, Y., Zhang, C., *Test Method for Fabric Bending Behavior Based on Image Processing*, In: Journal of Textile Research, 2013, 34, 7, 52–56

[28] Du, Z., Yu, W., Hamada, H., *Analysis of structure and bending property of spacer fabric composites*, In: Industria Textila, 2011, 62, 2, 64–71

[29] Du, Z., Shen, Hu., Zhou, T., Yu, W., *Comparison of properties characterization between CHES-FY, KES-F and FAST*, In: Industria Textila, 2011, 62, 3, 123–128

Authors:

DU ZHAOQUN[1], XU QIAOLI[2], GU LONGXIN[2], ZHENG DONGMING[3], WANG QICAI[4]

[1]Key Laboratory of Textile Science & Technology (Donghua University), Ministry of Education, College of Textiles,
Donghua University, 201620, Shanghai, China

[2]College of Textiles, Donghua University,
201620, Shanghai, China,
e-mail: 1159114@mail.dhu.edu.cn, 1169134@mail.dhu.edu.cn

[3]Jiangxi Provincial Center for Quality Inspection and Supervision on Down Products,
332020, Jiangxi Gongqingcheng, China
e-mail: zhongdm@139.com

[4]Lutai School of Textile and Apparel, Shandong University of Technology,
255000, Shandong Zibo, China
e-mail: qcwang@sdut.edu.cn

Corresponding author:

DU ZHAOQUN
e-mail: duzq@dhu.edu.cn