Compression property of three-dimensional honeycomb-structured fabric composites

Chunhong Zhu[1,2], Tokio Mori[1], Tatsuhiro Miyamoto[1], Sae Osaki[1], Jian Shi[3], Hideaki Morikawa[1,2]

[1] Graduate School of Science and Technology, Shinshu University, Ueda, Nagano, Japan

[2] Faculty of Textile Science and Technology, Shinshu University, Ueda, Nagano, Japan

[3] Faculty of Systems Science and Technology, Akita Prefectural University, Yurihonjo, Akita, Japan

Corresponding author:

Chunhong Zhu: zhu@shinshu-u.ac.jp

Jian Shi: shij@akita-pu.ac.jp

Abstract

In this study, a kind of honeycomb-structured woven fabric was investigated and the effect of yarn size and fabric layer on the compression property of the fabric-reinforced polyurethane elastomer composites was discussed. The honeycomb-structured fabric was analyzed from the cross-sectional view of combined regular hexagonal cells. The three-layer fabric and four-layer fabric were designed and fabricated using three different fineness of weft yarns. After that, polyurethane elastomer was used as matrix resin and the 3D honeycomb-structured fabrics were composited. In-plane compression test was conducted to investigate the cushioning property. For samples with doubled weft yarns, such as 3L-2W, the stress value when compressed to 65% of its initial thickness ($CV_{65\%}$), energy absorption (EA), and specific energy absorption (SEA) showed higher values than 3L-1W and 3L-1.5W. It was concluded that the weft yarn fineness had an important effect on the compression property of fabric composites. The thicker yarn size, the stronger cell wall, and the lightweight honeycomb-structure composite was difficult to be compressed. As to the fabric layers, three-layer composites showed a higher compression property than four-layer ones. The reason for this was considered to be the fiber volume content, which was the key parameter affecting composite mechanical properties. As the real fiber volume content in a three-layer fabric composite was higher than that of a four-layer fabric composite, it was resulted in a higher allowable safe stress and energy absorption ability. It can be concluded that the yarn fineness and fabric layers had an influence on the compression property, which can be seemed as the design parameters of honeycomb-structured fabrics for cushion applications.

Keywords:

3D honeycomb-structure fabric, fabric reinforced composite, yarn fineness, fabric layers, compression property

1 Introduction

Naturally, honeycomb is prepared by honeybees to store their honey and pollen, and it is the combination of hexagonal cells. The honeycomb structures are lightweight, with high strength, and less material. Inspired by honeycomb made by honeybees, the honeycomb structures were used as a core material in the sandwich structures, such as airplane, et al. Moreover, three-dimensional (3D) printed honeycomb sandwich structure[1], honeycomb cores[2] were also discussed.

Considering the honeycomb structure into fabrics, it can be considered as a 3D hollow fabric, categorized in the 3D fabric. 3D fabric was defined by Chen et al[3, 4], as either an overall 3D shape or a more complex internal 3D structure, or both. 3D fabrics[4] can further be divided into 3D solid fabrics, 3D hollow fabrics, 3D nodal fabrics and 3D shell fabrics. 3D fabrics are facilitated for technical applications, such as airframes, automobiles, et al. They[5] can be fabricated by a special loom, or Jacquard, dobby looms, which are used to increase fabric thickness.

3D hollow fabrics, also known as 3D cellular fabric, refer to a kind of woven fabric with a porous cross-section. Tao et al[6, 7] investigated grid-domed cellular textile composite and discussed their energy-absorption applications. They found that the cell diameter ratio of top to bottom and cell wall thickness were two important parameter of the energy-absorption property. Chen et al[8] explained the mathematically modelling of 3D hollow fabrics with different cross sections and introduced the design method. They proposed the algorithm and implemented in the CAD system for visualization. Li et al[9] developed 3D spacer fabric composites with integrated hollow core and demonstrated that the piles were important for the flatwise compression and shear. Behera et al[10] investigated the compressive property of spacer fabric composites with different cell shapes, such as rectangular, trapezoidal, and triangular. Results showed that the compression strength was primarily determined by the cell wall thickness and its angle with the horizontal fabric layer. Zhu et al[11] discussed the effect of design parameters of cellular circle-structured fabric composites on single beam loom for the cushioning usages. The results demonstrated that the circle cell size and fabric layers had an important effect on the in-plane compression property. However, for this structure, the resin-rich can be found between circle cells, which may influence the mechanical property of fabric composite.

3D honeycomb-structured fabric is a kind of 3D hollow fabric. As the honeycomb cells are connected to each other, resin-rich in the honeycomb structure is not happened. It is considered as an excellent structure for force dispersion. Chen[12-14] et al investigated the design method, manufacturing, and analysis of 3D honeycomb fabric composites, and discussed the structural parameters, such as cell opening angle, cell size, et al on the impact performance. However, during these researches, many of them were conducted on the hard materials for impact resistance applications, and little research was focused on their cushion application for apparel and home textiles. Actually, based on our previous study[11], the 3D hollow fabric composite can also be a potential material for elasticity and cushioning usages. Therefore, in this study, we proposed a kind of design method of 3D honeycomb-structured woven fabric, and composited with thermoplastic polyurethane elastomer (PU). Then the effect of weft yarn sizes and layers on the compression property was discussed.

2 Experimental

2.1 Honeycomb-structured fabric design and fabrication

The honeycomb structured was designed by bonding several regular hexagonal cells together at several hinges, as shown in Fig. 1(a). The structure can also be considered as five regular hexagonal cells bonded together at several hinges. The cell unit was formed by 6 walls, with the length defined as *l*.

The height of the cell h can be obtained from $2l\sin\theta$. This structure was defined as a three-layer honeycomb structure, and Fig. 1(b) showed the four-layer structure as well.

Based on the structure in Fig. 1(a), the cross-sectional view along the weft direction was shown in Fig. 2(a). Plain weave was used and the cell size *c* of the connection part was set to be the same as *l* as 4.5mm.

For fabrication, a Jacquard loom was used. Polyester spun yarn (50tex) was used as warp yarn, with the warp weave density as 24/cm. Polyester filament yarn (13.5tex×2) was used for weft yarn as original one, and the weave density in the weft direction was set to be 42.5/cm. Fig. 2 (b) shows the weave diagram of three-layer fabric sample when *l* was 4.5mm. Besides, four-layer fabrics shown in Fig. 1(b) were also fabricated. In order to investigate the effect of weft yarn fineness on the compression properties, 1.5 times (13.5tex×3) and doubled (13.5tex×4) original weft yarns were prepared and utilized in the fabrics. The fabric samples were defined as *n*L-*f*W, based on the fabric layers and the fineness of weft yarn. Here, *n* represented the number of layers, and L meant the layers, while *f* was the fineness of weft yarn compared to the original one, and W referred to the weft yarn. For example, 3L-1W referred to three-layer fabric with original weft yarn fineness. Thun, six kinds of honeycomb-structure fabric performs (3L-1W, 3L-1.5W, 3L-2W, 4L-1W, 4L-1.5W, 4L-2W) were prepared.

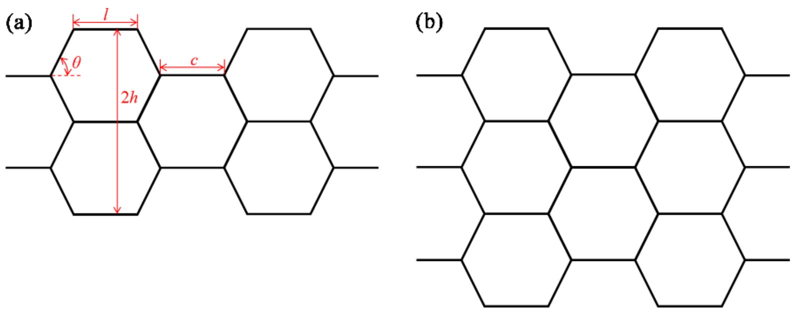

Fig. 1 The honeycomb structure. (a) a three-layer honeycomb structure; (b) a four-layer honeycomb structure.

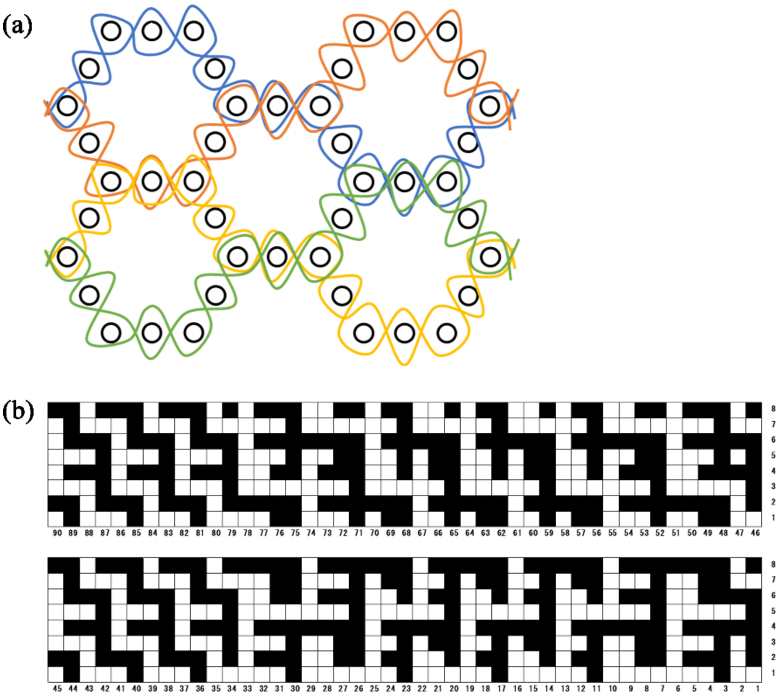

Fig. 2 The cross-sectional view of the three-layer fabric (a), and the weave diagram (b).

2.2 Manufacturing of honeycomb-structured fabric composite

The off-loom honeycomb-structure woven fabric was firstly expanded before impregnation. The hexagonal stainless rods were used to expand the fabric, and PU solution was used as resin for composite[11]. In order to extract the solvent, the pre-impregnated fabric was dried and cured at 160ºC in a vacuum environment for 1 hour. Fig. 3 demonstrated the real image of the fabric composite, as well as the x, y, and z directions.

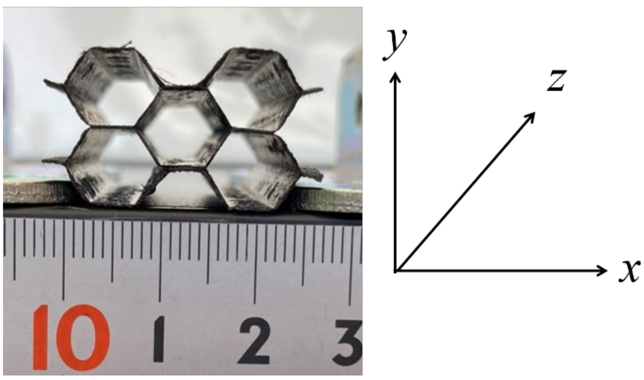

Fig. 3 The real image of the fabric composite

2.3 Evaluation of compression property

The compression property was evaluated by a universal testing machine (MCT-2150, A&D company, Ltd, Japan), with the schematic diagram shown in Fig. 4. The honeycomb fabric composite can be evaluated by compressing from x, y, or z directions[13], but in this study, the in-plane compression in the y direction was investigated for discussing its cushioning property. After sample was set onto the foundation, a compressor with the diameter of 60 mm was used with the compression speed of 10 mm/min. The strain-fixed evaluation method was adopted, and the maximum deformation of each sample was set to be 80% of their initial thickness.

As the durability was another important index for fabric composites for cushioning usage, the durability evaluation was conducted as well. Based on JIS K6400, composite sample was compressed up to 75% of their initial thickness, and kept for 72 hours with the compressor. After that, the compressor was withdrew and thickness (d_r) was measured after 30 minutes left at rest. The compressive residual strain (C_s) is adopted to evaluate the durability of fabric composite, and it can be calculated based on Equation (1).

$$C_s = \frac{d_0 - d_r}{d_0} \times 100 \qquad (1)$$

where d_0 refers to the initial thickness of fabric composite. The lower C_s indicates the composite a better compression durability.

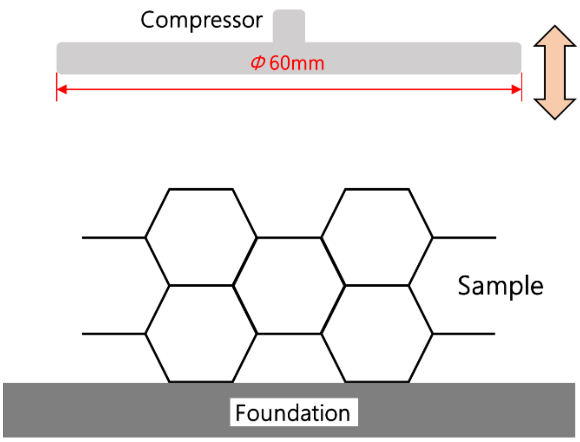

Fig. 4 Schematic diagram of the testing machine

3 Results and discussion

3.1 Effect of weft yarn thickness

In order to investigate the effect of weft yarn thickness on the compression properties, original, 1.5 times, and doubled weft yarns were applied to fabricate a three-layer (3L-*f*W) and four-layer (4L-*f*W) honeycomb-structured fabrics, and their compression property was evaluated after composited. The strain-stress curves of the three-layer fabric composites were shown in Fig. 5. As a whole, the results showed the same tendency: at first the strain increased with only a slight compression stress, after that the stress increased with small strain, then it changed slowly while strain was increased, and finally the stress was increased until the strain reached to 80%. The maximum stress during the compression process was different for each fabric composite. The 3L-2W fabric composite showed the largest maximum stress of 44.3 kPa, which was twice larger than 3L-1.5W, and three times larger than 3L-1W. This results meant that the 3L-2W fabric composite can endure the highest stress than the other two composite samples. The initial Young's modulus in the compression process from the slope of the S-S curve also showed that the 3L-2W fabric composite was the most difficult to compress. These results showed that the fineness of weft yarn had an important effect on the compression property of 3D honeycomb-structured fabric composite.

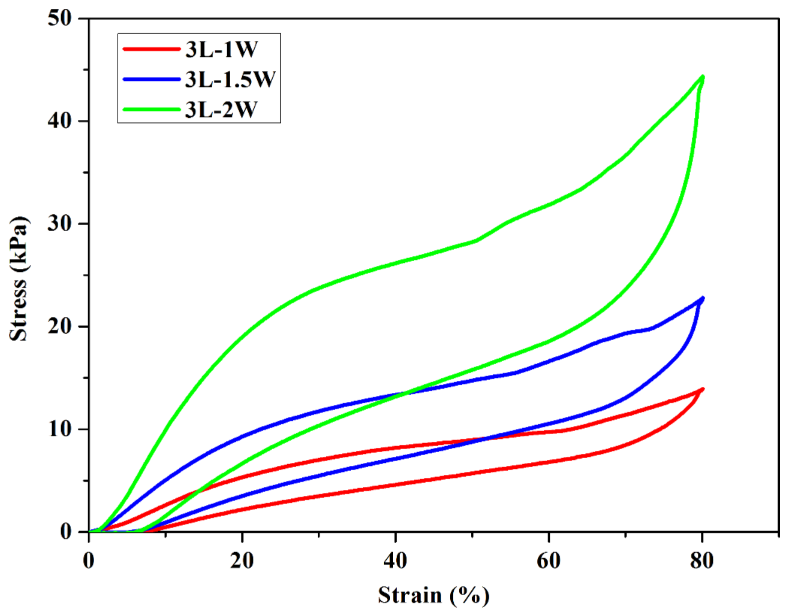

Fig. 5 The strain-stress curves of the three-layer fabric composites

Similar results can also be found for the four-layer fabric composites as shown in Fig. 6. For the four-layer fabric composites, effect of the weft yarn fineness on the compression property had also been investigated. The maximum stress of the 4L-2W fabric composite was 30.7 kPa, while that of the 4L-1.5W and 4L-1W were 16.4 and 13.7 kPa, respectively. The fiber volume content is an important parameter affecting the mechanical property of composites. The value of the (3L-*f*W) honeycomb-structured fabric composite was estimated from approximately 16.4% to 20.5% with the increase of weft yarn thickness. Even though the fiber volume contents of these composites were lower than the traditional carbon fiber reinforced epoxy plastic formed by VARTM and needed to be improved from the weave density, deformation method, as well as interface between fibers and resin, it was suggested that in the same dimension of fabric, coarser weft yarns means dense array of yarns, and therefore increase the fiber volume content in the same honeycomb structure, resulting in a larger compression force. These results indicated that coarser weft yarns can improve the compression property of fabric composite.

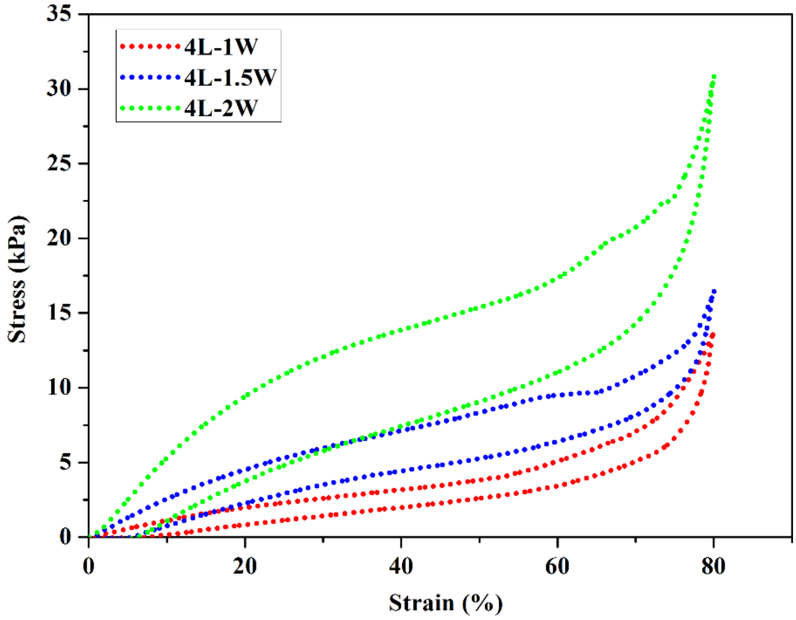

Fig. 6 The strain-stress curves of the four-layer fabric composites

3.2 Effect of fabric layers

Fig. 7 showed the strain-stress curve of *n*L-1.5W fabric composites. The difference of the maximum stress and initial Young's modulus for the 4L-1.5W fabric composites was smaller than that of the 3L-1.5W fabric composite, as well as the other two fabric composites groups with different *n*. The reason for this phenomenon can be explained by the change in the weave density of each fabric layer. As the total weave density in both the warp and weft directions were not changed with fabric layers, weave density of each layer for three and four-layer fabric was different. The density of three-layer fabrics was higher than that of the four-layer fabric, and its compression property was higher than that of four-layer ones. Thicker yarn size combined to a stronger cell walls, showing that the lightweight honeycomb composite to be difficult to be compressed.

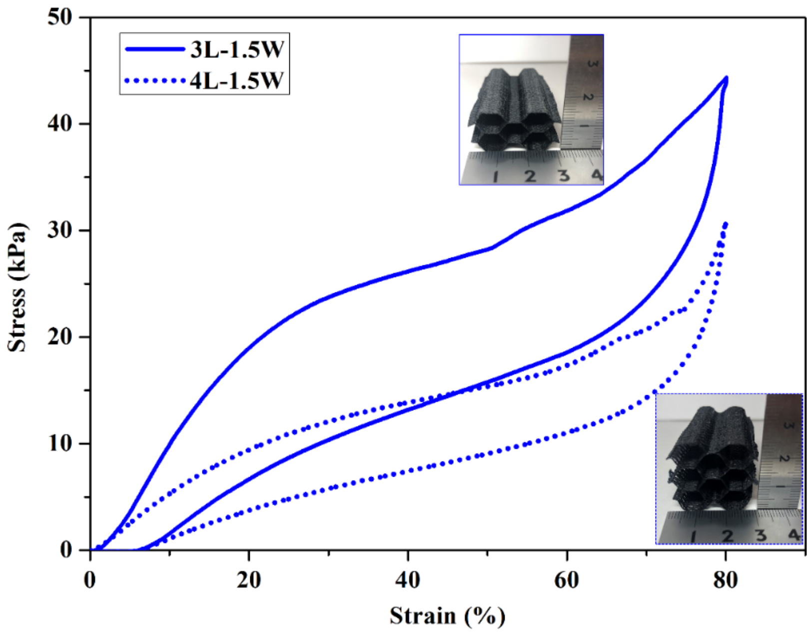

Fig. 7 The strain-stress curves of the *n*L-1.5W fabric composites

3.3 Discussions on the compression deformation

In order to evaluate the compression property of honeycomb-structured fabric composites, the following parameters are applied based on the compression and recovery curve. $CV_{65\%}$ is the stress value when the composite sample is compressed to the 65% of its initial thickness. It can be seemed as a permissible safe compression stress for the composite sample. Another parameter is the energy absorption (EA) capacity, referring to the ability of composite for absorbing kinetic impact energy during the compression process. It is calculated as the area of the force-displacement curve shown in Equation (2).

$$\mathrm{EA} = \int_0^{t_{max}} F dt \tag{2}$$

where *t* represents the displacement, t_{max} is the maximum compression displacement and *F* denotes the load of compression.

The third parameter is known as the specific energy absorption (SEA)[15], which is obtained from Equation (3).

$$\mathrm{SEA} = \frac{EA}{m} \tag{3}$$

where m refers to the mass of the honeycomb-structured fabric composite. Generally, the higher value of SEA represents the better energy absorption capacity of the composite.

The last parameter is the compression resilience (CR), which is used to evaluate the hysteresis loss, and it can be calculated from Equation (4).

$$CR = \frac{S_u}{S_l} \times 100\% \quad (4)$$

S_l refers to the area during the loading process, while S_u is determined from the unloading process. Higher CR means a higher recovery property with lower hysteresis loss.

The results of $CV_{65\%}$, EA, SEA, and CR are summarized in Fig. 8-11. The $CV_{65\%}$, EA, and SEA showed increased results with the increase of fineness in weft yarn, such as 3L-1W, 3L-1.5W, and 3L-2W. The same tendency can also be found in the four-layer fabric composites. For fabric composites with the same layers, the fineness of weft yarns can be seemed as an important factor affecting the allowable safe stress. On the other hand, the increased fabric layers cannot improve the $CV_{65\%}$, EA, and SEA from this investigation. The reason for this result was considered to be the weave density of fabric. As the total weave density was the same, the fiber volume contents in a four-layer fabric composite were approximately 11.0% to 15.1%, which were lower than that of a three-layer fabric composites. It resulted in a lower allowable safe stress and energy absorption ability. CR of 3-layer fabric composites showed the opposite results as $CV_{65\%}$, EA, and SEA. 3L-1W fabric composite showed higher CR than 3L-1.5W and 3L-2W, represented a higher recovery property than the other two samples. However, for the 4L-*f*W composites, results demonstrated higher value than that of the 3L-*f*W samples. As CR was influenced by both the compression process and the recovery process, composites with higher energy absorption property showed lower recovery property.

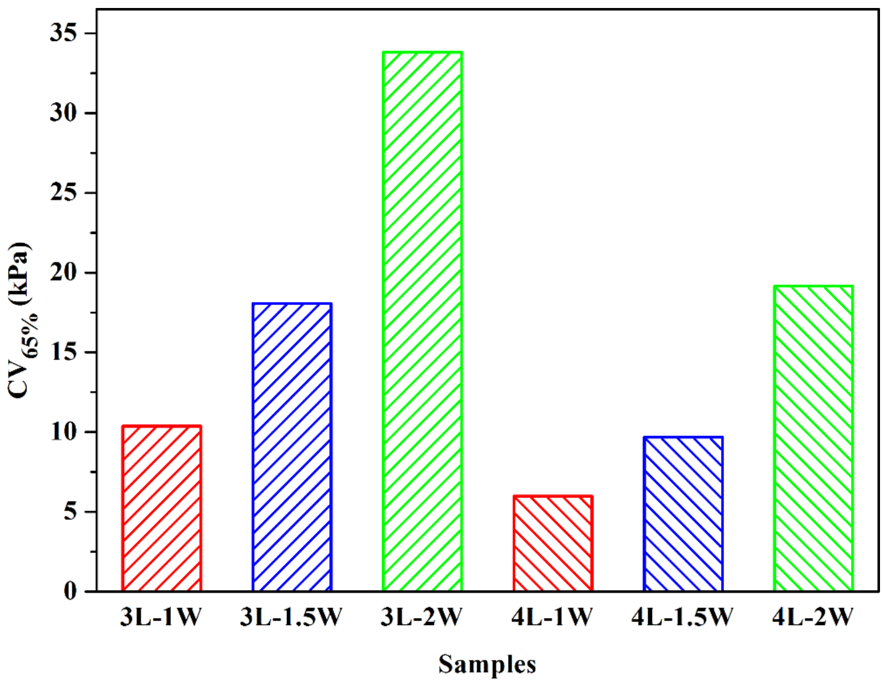

Fig. 8 Results of $CV_{65\%}$ of six honeycomb-structured fabric composites

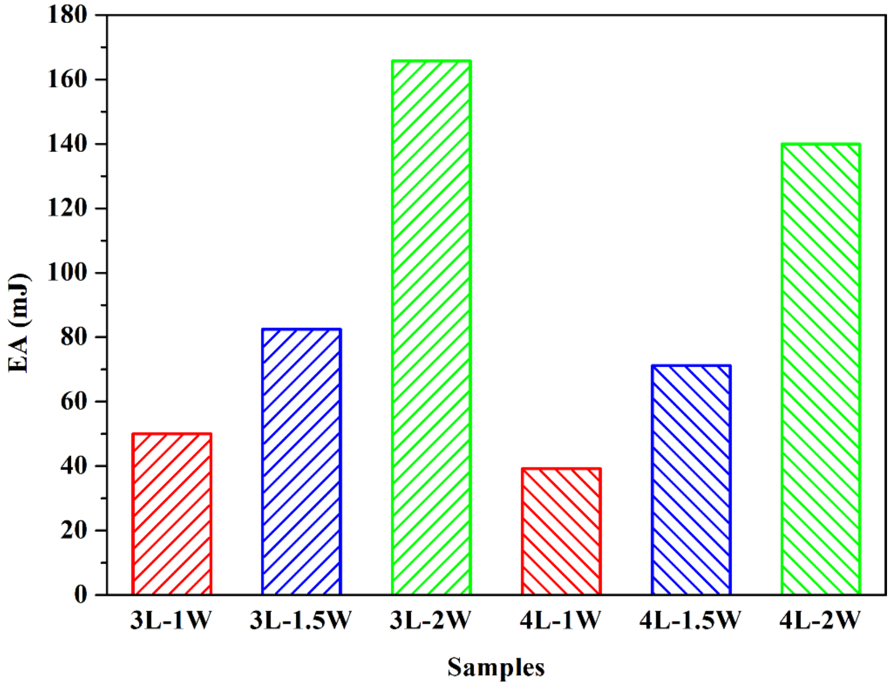

Fig. 9 Results of EA of six honeycomb-structured fabric composites

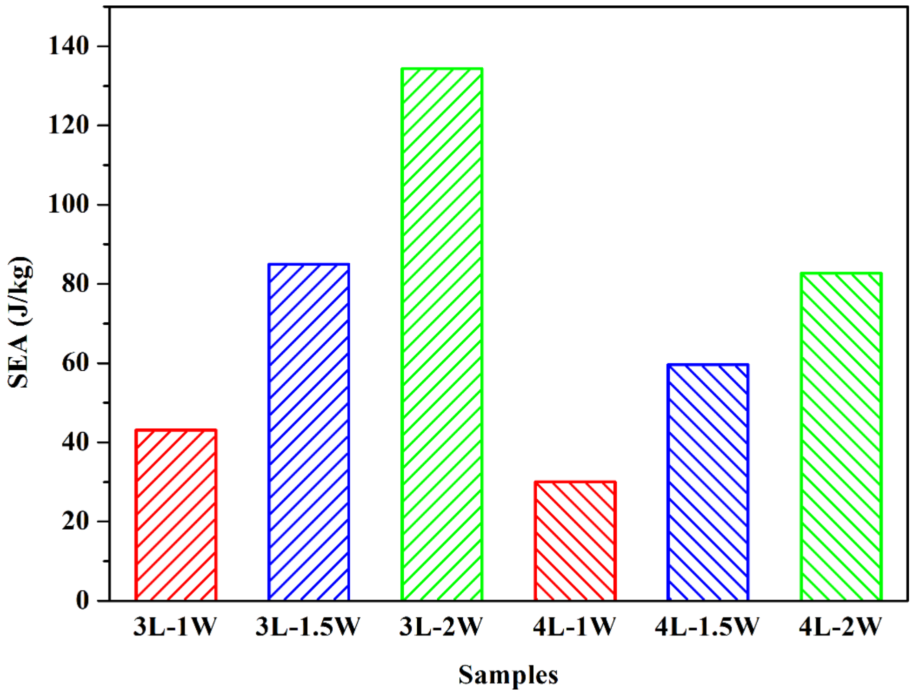

Fig. 10 Results of SEA of six honeycomb-structured fabric composites

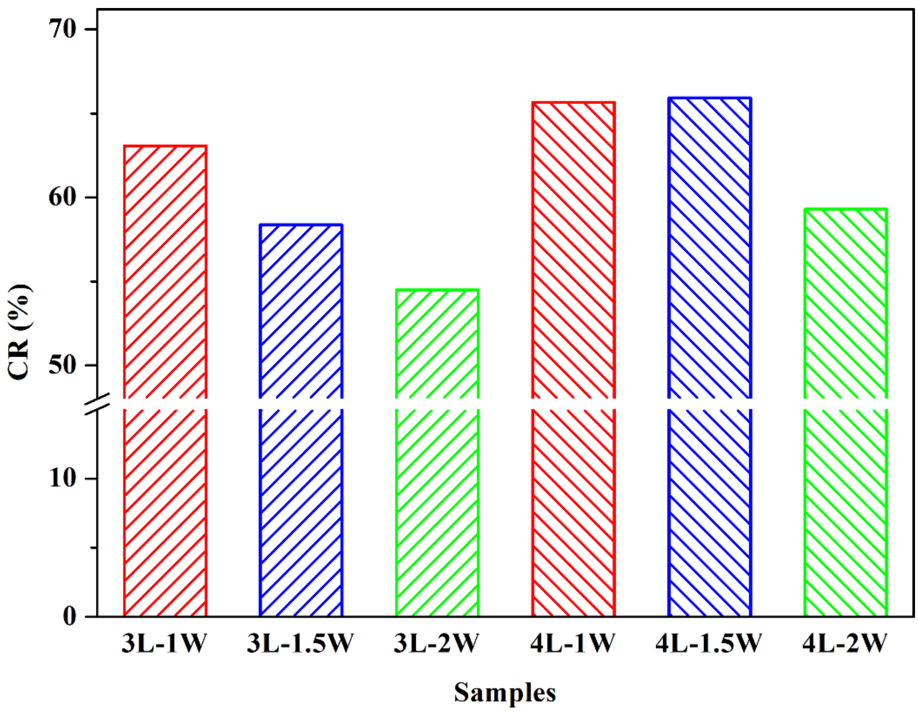

Fig. 11 Results of CR of six honeycomb-structured fabric composites

For the honeycomb structure, when one cell was loaded, it had many directions of force distribution, which meant less load on one cell, therefore it was strong against impact. In order to investigate the deformation of the honeycomb-structured fabric composite according to the load, Fig. 12 summarized the deformation of honeycomb cells as well as the real compression images. At (a), the honeycomb cell was compressed and a slight elastic deformation was observed, however, at this time, size of the honeycomb cell was not changed. Continue to be compressed from (b) to (e), elastic hinges at the joints enabled the cell to deform[16] by changing the cell angle until the fabric composite was crushed. It can be the reason of the honeycomb structure deformation. When loaded in the in-plane direction, the honeycomb structure was deformed by flexing and stretching the cell wall, as well as by hinging at the cell wall joints[16].

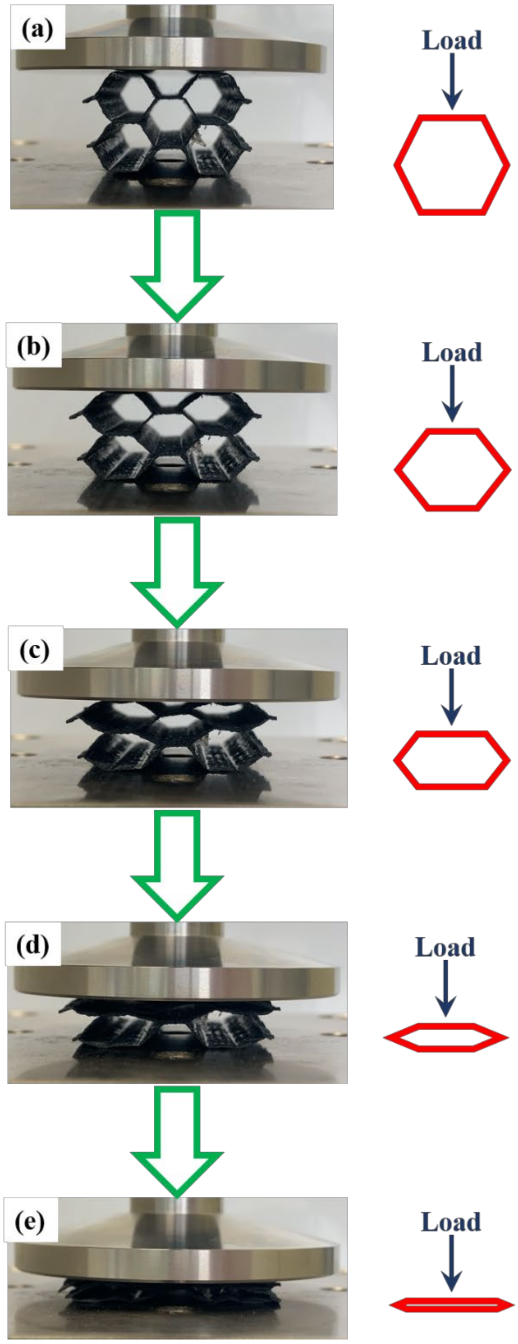

Fig. 12 Deformation mechanism and images of honeycomb cells

3.4 The durability of fabric composites

The durability of fabric composites was also important for materials with cushioning properties. The results of compressive residual strain (C_s) is shown in Table 1. All samples showed the value between 13% and 20%, and it was difficult to conclude that there had some relationships between weft yarn fineness and durability, as well as the fabric layers and durability. For the durability of fabric composites, it is necessary to discuss in detail in the future work.

Table 1. The C_s of six fabric composites

Samples	C_s (%)
3L-1W	13.5
3L-1.5W	19.4
3L-2W	17.1
4L-1W	16.9
4L-1.5W	16.9
4L-2W	17.3

4 Conclusion

The purpose of this research was to investigate a new application of 3D honeycomb-structured fabric for cushioning usages. In order to achieve the purpose, in this study, a kind of honeycomb-structured woven fabric was investigated and composited using PU as resin. The effect of weft yarns and fabric layers on the compression property were discussed.

The honeycomb-structured fabric was proposed by binding regular hexagonal cells together. The three-layer fabric and four-layer fabric were design and fabricated using three different fineness of weft yarns. After that, PU was used as matrix resin and the 3D honeycomb-structured fabrics were composited. Compression test in the in-plane direction was conducted to investigate the cushioning property. The results revealed that the weft yarn fineness had an important effect on the compression property of fabric composites. For samples with doubled weft yarns, such as 3L-2W, and 4L-2W, the $CV_{65\%}$, EA, and SEA showed higher values than *n*L-1W and *n*L-1.5W. As the thicker yarn size combined to a stronger cell walls, resulted in the lightweight honeycomb composite to be difficult to be compressed. As to the fabric layers, 3L-*f*W composites showed a higher compression property than 4L-*f*W. The reason for it was considered as the fiber volume content, which was key parameter affecting composite mechanical property. As the total weave density was the same, the fiber volume content in a three-layer fabric composite was higher than that of a four-layer fabric composite, which resulted in a higher allowable safe stress and energy absorption ability. The durability of fabric composites was also discussed with compressive residual strain as an index. Six samples showed the value from 13% to 20%, and it was difficult to determine the relationships between weft yarn fineness and durability.

From this study, it can be concluded that the weft yarn size and fabric layer had an influence on the compression property of composite. For 3D fabric design, the above two parameters should be considered to satisfy the need for practical use.

Acknowledgements

This work was supported by JSPS KAKENHI (Grant number JP19K14032, JP20H00288).

Data Availability Statements

The datasets generated during and/or analyzed during the current study are not publicly available due to the patent application but are available from the corresponding author on reasonable request.

References

1. Antony S, Cherouat A and Montay G: Fabrication and Characterization of Hemp Fibre Based 3D Printed Honeycomb Sandwich Structure by FDM Process. Appl Compos Mater. **27**, 935-953 (2020)
2. Aminanda Y, Castanié B, Barrau JJ and Thevenet P: Experimental Analysis and Modeling of the Crushing of Honeycomb Cores. Appl Compos Mater. **12**, 213-227 (2005)
3. Chen X: Advances in 3D Textiles. 1st ed. Woodhead Publishing, Cambridge (2015)
4. Chen X, Taylor LW and Tsai L-J: An overview on fabrication of three-dimensional woven textile preforms for composites. Text Res J. **81**, 932-944 (2011)
5. Khokar N: 3D-Weaving: Theory and Practice. J Text I. **92**, 193-207 (2001)
6. Tao XM, Xue P and Yu TX: New Development of Cellular Textile Composites for Energy-Absorption Applications. J Ind Text. **33**, 15-31 (2003)
7. Lam SW, Tao XM and Yu TX: Comparison of different thermoplastic cellular textile composites on their energy absorption capacity. Compos Sci Technol. **64**, 2177-2184 (2004)
8. Chen X and Wang H: Modelling and computer-aided design of 3D hollow woven reinforcement for composites. J Text I. **97**, 79-87 (2006)
9. Li M, Wang S, Zhang Z and Wu B: Effect of Structure on the Mechanical Behaviors of Three-Dimensional Spacer Fabric Composites. Appl Compos Mater. **16**, 1-14 (2008)
10. Neje G and Behera BK: Lateral Compressive Properties of Spacer Fabric Composites with Different Cell

Shapes. Appl Compos Mater. **25**, 725-734 (2018)

11. Zhu C, Shi J, Hayashi K, Morikawa H, Sakaguchi A and Ni Q: Effect of design parameters on the cushioning property of cellular fabric composites. Text Res J. **89**, 3692-3699 (2018)
12. Chen X, Sun Y and Gong X: Design, Manufacture, and Experimental Analysis of 3D Honeycomb Textile Composites Part I: Design and Manufacture. Text Res J. **78**, 771-781 (2008)
13. Chen X, Sun Y and Gong X: Design, Manufacture, and Experimental Analysis of 3D Honeycomb Textile Composites, Part II: Experimental Analysis. Text Res J. **78**, 1011-1021 (2008)
14. Tan X and Chen X: Parameters affecting energy absorption and deformation in textile composite cellular structures. Mater Design. **26**, 424-438 (2005)
15. Ufodike CO, Wang H, Ahmed MF, Dolzyk G and Jung S: Design and modeling of bamboo biomorphic structure for in-plane energy absorption improvement. Mater Design. **205**, 109736 (2021)
16. Masters IG and Evans KE: Models for the elastic deformation of honeycombs. Compos Struct. **35**, 403-422 (1996)