Development and analysis of a three-dimensional braided honeycomb structure

Li, Qianqian; Zhang, Honghua; Mosleh, Yasmine; Alderliesten, René; Li, Wei

DOI
10.1177/00405175221139578

Publication date
2022

Document Version
Final published version

Published in
Textile Research Journal

Citation (APA)
Li, Q., Zhang, H., Mosleh, Y., Alderliesten, R., & Li, W. (2022). Development and analysis of a three-dimensional braided honeycomb structure. *Textile Research Journal*, *93*(9-10), 2078-2094. https://doi.org/10.1177/00405175221139578

Textile Research Journal

Original article

Textile Research Journal
0(0) 1–17

DOI: 10.1177/00405175221139578
journals.sagepub.com/home/trj
SAGE

Development and analysis of a three-dimensional braided honeycomb structure

Qianqian Li[1], Honghua Zhang[1], Yasmine Mosleh[2], René Alderliesten[2] and Wei Li[1]

Abstract

This paper presents the design and development of three-dimensional braided honeycomb structures. The basic principles and braiding process are described. The relationship between braiding parameters and honeycomb geometric parameters is established and several three-dimensional (3D) braided honeycomb fabrics are introduced. Based on the principle of the 3D braiding 'four-step' method, the interlaced state of yarns can be changed by controlling the movement of yarn carriers, so the separation and combination of the braid can be controlled, then 3D braided honeycomb fabric can be formed. As the number of braiding cycles of wall length increases, the relative density will gradually decrease, but the number of braiding cycles of free wall length has a greater effect on the relative density. When the number of columns of yarns participating in wall thickness increases, the relative density will gradually increase. The relative density also showed a positive correlation with the braiding angle. With the increase of the opening angle, the relative density gradually decreases, although there is a minimum point after which a little increase is observed. This paper provides significant guidance for designing various 3D braided honeycomb structures and evaluating their relative density, and can be a reference for the design and development of new honeycombs structures.

Keywords

3D braiding, honeycomb, relative density, Jute

As a major cellular structure, the honeycomb structure is widely used in various fields such as aerospace,[1–4] automotive,[5–7] marine,[8,9] architecture, and mechanical engineering because of its superior specific mechanical properties,[10,11] and excellent designability.[12,13] In recent years, the honeycomb structure has entered a multi-functional, multi-field, and multi-scale rapid development stage.[14] Honeycomb structures can be made from different materials, including metal,[15,16] paper,[17,18] and polymers. However, fiber-reinforced composite honeycomb with lightweight and excellent mechanical performances has attracted noticeable attention.[12]

Fiber-reinforced composite materials have higher specific strength and specific stiffness and are also superior in corrosion resistance and durability than traditional materials such as aluminum and steel.[12] Fibers are also divided into chemical fibers and natural fibers. The production, processing, and post-processing of chemical fibers can cause environmental problems.[19] But natural fibers are eco-friendly, recyclable, and biodegradable by nature,[20] which conforms to the trend of recent developments in environmental policies in today's world, and has received ever-increasing attention.[21,22] Therefore, it is of certain significance to develop new honeycomb structures using natural fibers.

There are also various techniques for fabricating honeycomb structures. Wei et al.[12] summarized fiber-reinforced honeycomb structures into the following categories according to manufacturing technology and related unit configurations: hot press molding method,[21,23] vacuum-assisted resin transfer molding

[1]Donghua University, China
[2]Delft University of Technology, Netherlands

Corresponding author:
Wei Li, Donghua University Room 3013, No.3 College Building 2999 Renming N. Rd., Shanghai, ShangHai 201620 China 021-67792636.
Email: liwei@dhu.edu.cn

(VARTM) method,[20] interlocking method,[24] three-dimensional (3D) printing method,[25] tailor-folding method.[26] For the interlocking method, the rib intersections can result in a weak place where failure can initiate, and stiffness reductions may occur.[12] For the tailor-folding method, under the action of mechanical loading, cracking will occur at the bonding place.[12] Therefore, an integral honeycomb structure need to be developed to avoid delamination and weak joints. Textile honeycomb composite has a promising future because these structures can provide improved structural integrity.[11]

Many researchers also used textile techniques to form honeycomb fabric composites. Kamble et al.[27] designed and developed the woven textile-based structural hollow composites, established that the number of crossover points in the weave structures offered excellent association with the impact energy absorption and formability behavior, and revealed that the specific compression energy is higher for regular honeycomb structures with smaller cell sizes and a greater number of layers keeping constant thickness. Xiao et al.[28] weaved six kinds of honeycomb fabrics to validate his analytical model that characterizes the geometrical shape and position of each yarn in a honeycomb fabric unit-cell and the volume of the internal space. The experimental results show that the volume of the internal space decreases with the increase of fabric density, and the application of the elastic yarns to the fabric reduces the volume significantly. Chen et al.[29] has also designed and woven honeycomb fabrics and has established an algorithm for fabric and composite design. They studied the influence of structural parameters, including cell opening angle, cell size, cell wall ratio, and the cell density for the same cross-sectional area, to characterize the 3D honeycomb composites systematically. It was found that changes in structural parameters affect impact energy absorption and impact force attenuation. The effect of the volume density of the honeycomb composites on impact characteristics was also investigated. The results indicate that while the volume density has little effect on the energy absorption, it has a significant influence on the transmitted force.[30] Tripathi et al.[31] designed a 3D woven honeycomb structure based on textile fibers using fabric geometric parameters. And mathematical expressions are established to calculate the repeat unit weight, fiber volume fraction (FVF), and specific gravity of the 3D woven honeycomb structure. It is concluded that with an increase in the number of picks in both free wall and bonded wall, repeat unit weight increases whereas fiber volume fraction and specific weight of the honeycomb cell decrease. Antony et al.[32] compared conventional aluminum-based honeycomb structures and hemp fiber woven fabrics-based honeycomb sandwich structures and found the good potential of hemp-based honeycomb structures to be used in many applications in aircraft or automotive interior parts. It can be seen from the above that the parameters during the manufacturing of honeycomb fabrics will affect geometrical parameters within the honeycomb structure, which in turn has an important impact on the mechanical properties of the honeycomb composites. Therefore, it is very important to establish the relationship between braiding parameters and geometric parameters of honeycomb fabrics, and then explore the influence of different configurations on the mechanical properties.

At present, the development of honeycomb structures by textile technology is mostly concentrated on woven fabrics, but the exploration of braided honeycomb fabrics is reported less. However, the braided composite has resistance to delamination because its internal yarns are intertwined to form a tight spatial network structure.[33,34] Furthermore, 3D braided composites have good impact damage tolerance, greatly superior crashworthiness properties, and are less sensitive to notches. Therefore, using 3D braiding technology to realize the honeycomb structure according to reasonable design, the integrity of 3D braiding and the lightweight characteristics of honeycomb structure can be fully utilized.

The research can be divided into two parts; one part is how to design 3D braided honeycomb fabrics in different shapes and configurations. The second part is which 3D braided honeycomb fabric has more advantages in the performance of the composite material, so the fabric can be improved and optimized through the first part. This paper focuses on the first part. Apart from introducing the basic principles of braiding process and the design and manufacturing of 3D braided honeycomb structures, this paper aims to establish the relationship between braiding parameters and honeycomb geometric parameters, so as to design 3D braided honeycomb structures with different shapes and specifications. This will provide design guidelines for manufacturing these braided honeycombs for different application backgrounds.

1. Braiding principle and braiding process

1.1 The principle of 3D braided honeycomb fabrics

The 3D braided honeycomb fabric is realized on a self-made 3D braiding set-up based on the principle of the 3D braiding 'four-step' method,[35] as shown in Figure 1[36] and Figure 2. The preform being braided is hung above the machine bed on which yarn carriers are arranged in a prescribed pattern. Braiding is realized through the permutation of yarn carriers on a machine bed by row and column trace movements in the X- and Y-direction, respectively, and the preform is fabricated in the Z-direction.[35,36]

The braiding yarns move from the interior to the surface, then change direction and return to the interior region, the trace of surface yarns connects with the internal yarn trace.[37] Side yarns only participate in the movement in one direction (left–right movement or forward–backward movement). Therefore, if the yarns are not braided with another column of yarns, they act like side yarns and only move in one direction. When the yarns are arranged like Figure 3(a), the yarns of column 2 only move left and right instead of forward and backward. When the yarns in column 1 move to column 2, they will return to column 1 and not move to column 3, and not braid with the yarns in column 3. Similarly, when the yarns of column 3 move to column 2, they will also return to column 3, not move to column 1, and not braid with the yarns of column 1. So, the yarns of column 2 act as side yarns of the first and third column of yarns, forming a two-part independent braiding structure (Yarns for each part are represented by a different color.) These two parts of yarns are not interlaced (Figure 3(b) shows the yarn trace), resulting in a layered braiding fabric structure.

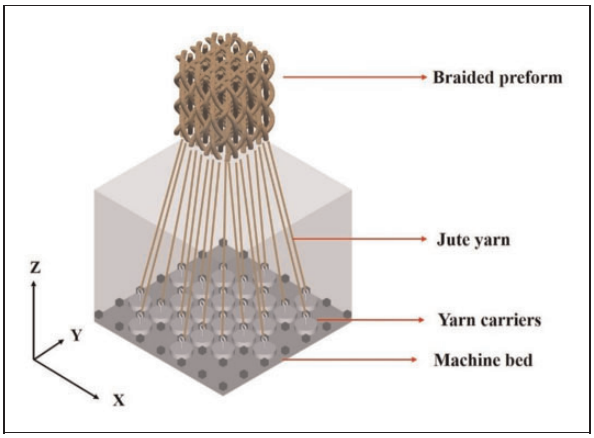


Figure 1. Schematic of three-dimensional (3D) braiding set-up.[36]

By summarizing the regularity of yarn movement, the interlaced state of yarns can be changed so that the separation and combination of the braid can be controlled:[38] When the braid needs to be separated, the yarns in the middle column are used as side yarns, and only move left and right, not forward and backward. When the braid is combined, the yarns in

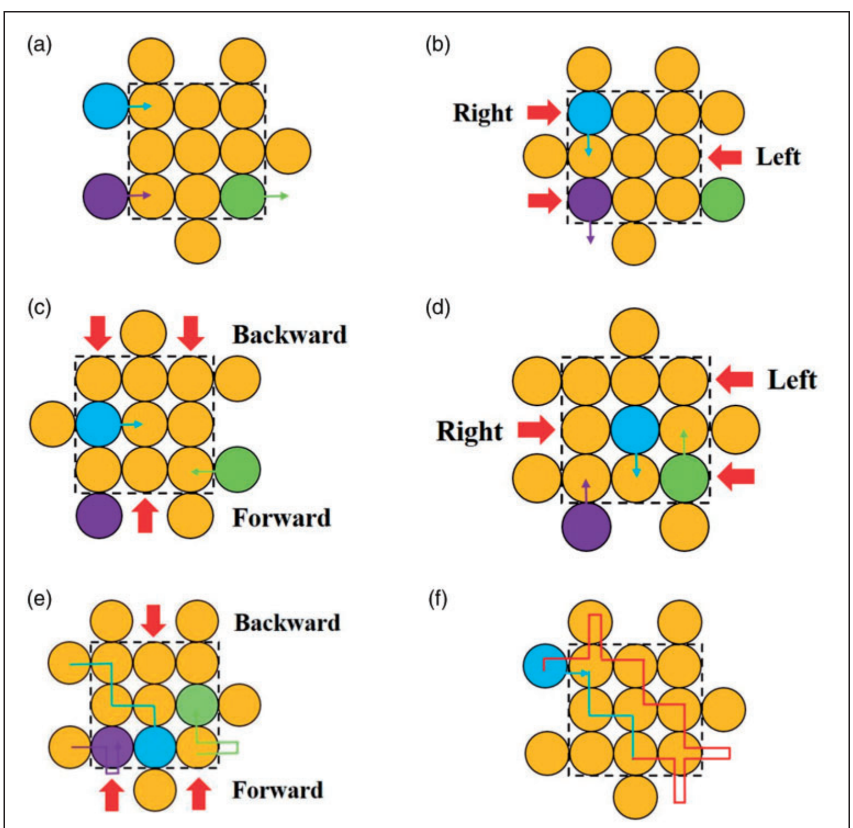


Figure 2. Scheme of 'four-step' braiding method[35] and the movement trace of one of the yarns (The yarns in black dashed box are called main yarns in the interior, and the yarns outside black dashed box are called side yarns on the surface.). a) Original; (b) first step; (c) second step; (d) third step; (e) fourth step and (f) the movement trace of a yarn.

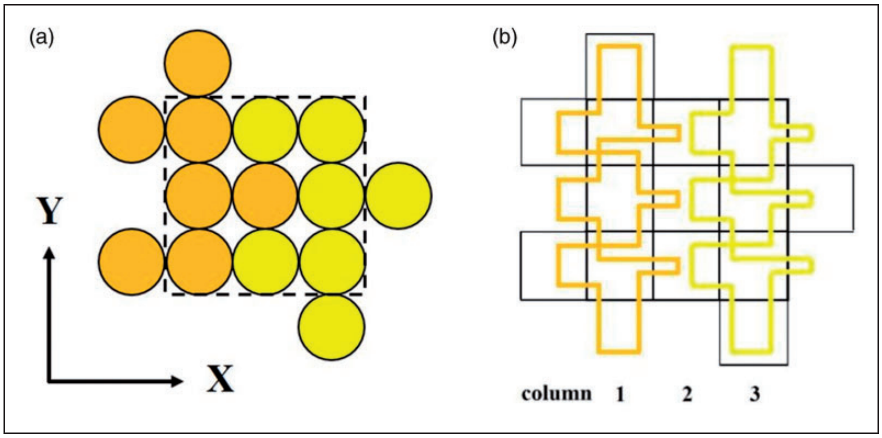


Figure 3. Braiding regularity of layered fabric. (a)The permutation of yarns and (b) the movement trace of one yarn in each part.

the middle column are used as main yarns for normal braiding movement.

1.2 Braiding process

To make hexagon continuous, two separately braided stripes need to be braided together. The yarns originally used for side yarns are used as main yarns to braid (move backward and forward, left and right). Therefore, the yarn permutation of 3D braided honeycomb fabrics is the same as that of the rectangular braiding. Just control whether this column of yarns moves backward and forward.

As shown in Figure 4,[8] every circle represents a carrier carrying a yarn. The number of yarns:

$$N = m \times n + m + n = 23 \times 5 + 23 + 5 = 143$$

m is the number of columns in the X-direction and n is the number of rows in the Y-direction. Blue yarns and yellow yarns represent a group of yarns, respectively. Every wall of the hexagonal honeycomb is braided by a group of yarns. The white circle means that this yarn is not involved in braiding. The yarns in the column of red box only move left and right without forward and backward, which are equivalent to the role of side yarns. The four parts 1/2/3/4 in Figure 4 form walls of the honeycomb structure. Every part is braided according to the 3D braiding 'four-step' method. There are some floating yarns on the upper and lower surfaces of the honeycomb structure fabric because the process of braiding separately braided stripe has yarns that do not participate in braiding. The floating yarns in the forward movement direction of yarn carriers are the upper floating yarns, and the floating yarns in the backward movement direction of yarn carriers are the lower floating yarns.

The wall thickness of the honeycomb fabric in Figure 4 is braided with two columns of yarns. Using the same number of yarns and the same permutation, the number of columns of yarns braiding every braided stripe varies, then the wall thickness of the honeycomb structure and the number of cells will be different. As shown in Figure 5, the wall thickness of the honeycomb structure is braided with three columns of yarns, and the number of columns of cells is three. The wall thickness of the honeycomb structure in Figure 6 is braided with five columns of yarns, and the number of columns of cells is two.

2. Braiding parameters and honeycomb geometric parameters

The dimension of a honeycomb fabric along $X/Y/Z$ directions are defined as width, height, and length, respectively, as shown in Figure 7. The separate braided strips are named free walls, and the braided strips that combine the separate strips are called joint walls. The angle between two free walls of a hexagonal cell is defined as the opening angle. The braiding cycles constituting the length of free wall and joint wall are f_1 and f_2, respectively. The description of parameters is shown in Table 1. The number of columns of yarns for braiding free wall thickness and joint wall thickness are m_1 and m_2, respectively. Furthermore, m_1 and m_2 should satisfy:

$$m_2 = 2 \cdot m_1 + 1$$

To make unit cells of a 3D braided honeycomb fabric complete, m and m_1 should satisfy:

$$m + 1 = k \cdot (m_1 + 1)$$

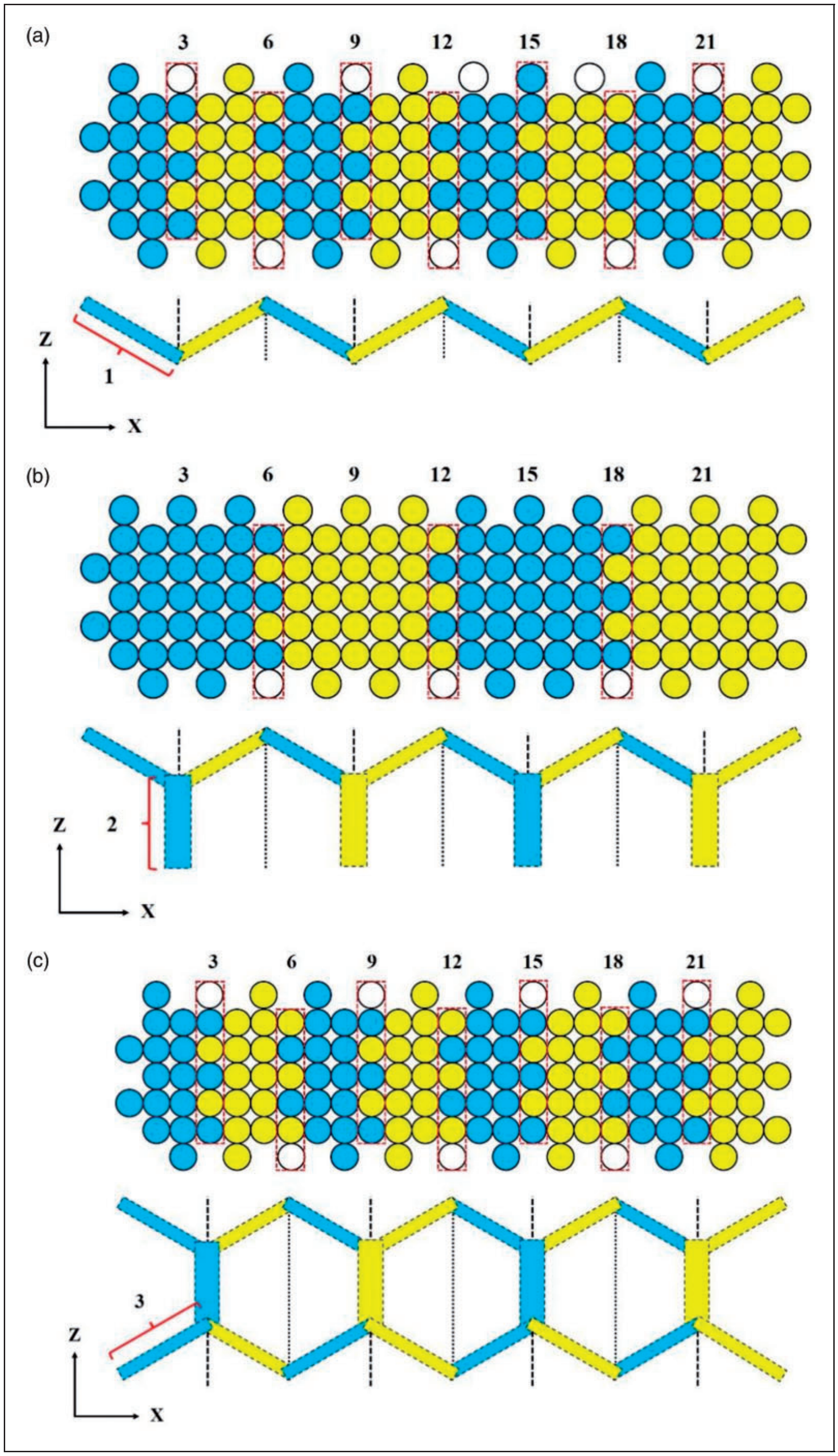


Figure 4. Schematic diagram of the yarn permutation and the braiding process of a three-dimensional braided honeycomb structure fabric with a wall thickness of two columns of yarns.[38] (a)The yarns in columns 3/6/9/12/15/18/21 act as side yarns, and only move left and right, not forward and backward. The braiding yarns are divided into eight braided strips; (b) the yarns in columns 6/12/18 still play the role of side yarns, the yarns in columns 3/9/15/21 act as main yarns to combine the eight braided strips in (a) into four braided strips; (c) the same as (a), the four braided strips combined in (b) are divided into eight braided strips and (d) the yarns in columns 3/9/15/21 are used as side yarns, while the yarns in columns 6/12/18 are used as main yarns. The braiding yarns are combined into five strips.

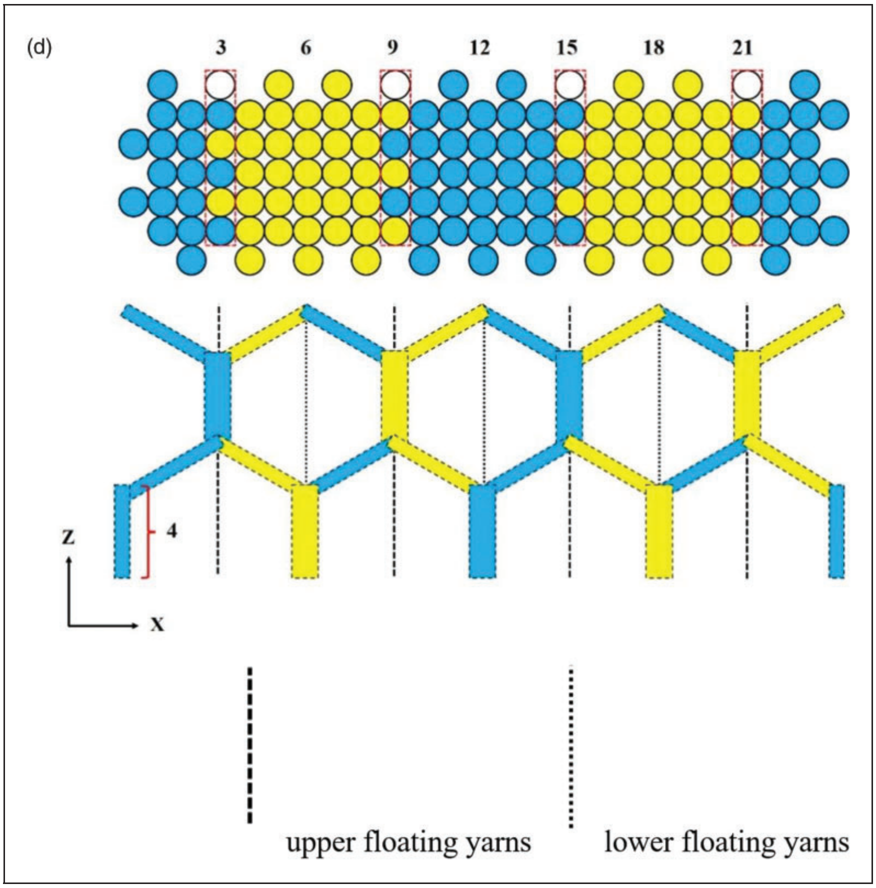


Figure 4. Continued.

where k is a positive integer, usually an even number, and $k \geq 4$. When $k < 4$, two complete hexagonal unit cells cannot be formed. If k is an odd number, there is a half hexagonal unit cell in each row.

2.1 Braiding parameters and honeycomb geometric parameters

The internal structure of 3D braided preform is a little complex. Only by knowing the relationship between braiding structure and braiding parameters, can we better understand the relationship between braiding parameters and honeycomb geometric parameters. Combined with the three types of microstructural unit-cell models established by Chen et al.[35] and the principle of 3D braiding 'four-step' method,[35] the motion trace of yarns can be drawn in Figure 8.

These models simulate the microstructure of the braided composites. When analyzing the geometry of the braided preform, the assumptions and calculation formulas described by Chen et al. are used.[35] So the width and the thickness of the 3D braided preform are given as

$$W_x = \frac{\sqrt{2}m + 2 - \sqrt{2}}{4} \cdot h \cdot \tan\gamma = \frac{m + \sqrt{2} - 1}{2} \cdot h \cdot \tan\alpha \quad (1)$$

$$W_y = \frac{\sqrt{2}n + 2 - \sqrt{2}}{4} \cdot h \cdot \tan\gamma = \frac{n + \sqrt{2} - 1}{2} \cdot h \cdot \tan\alpha \quad (2)$$

where W_x and W_y are width and thickness of a 3D braided preform, respectively, m is the number of columns and n is the number of rows, h is the pitch length of braiding one cycle, γ is interior braiding angle, α is called the braiding angle which is formed by the grain of the preform surface. The cross-section of braiding yarns is elliptical with major and minor radius, a and b, respectively.

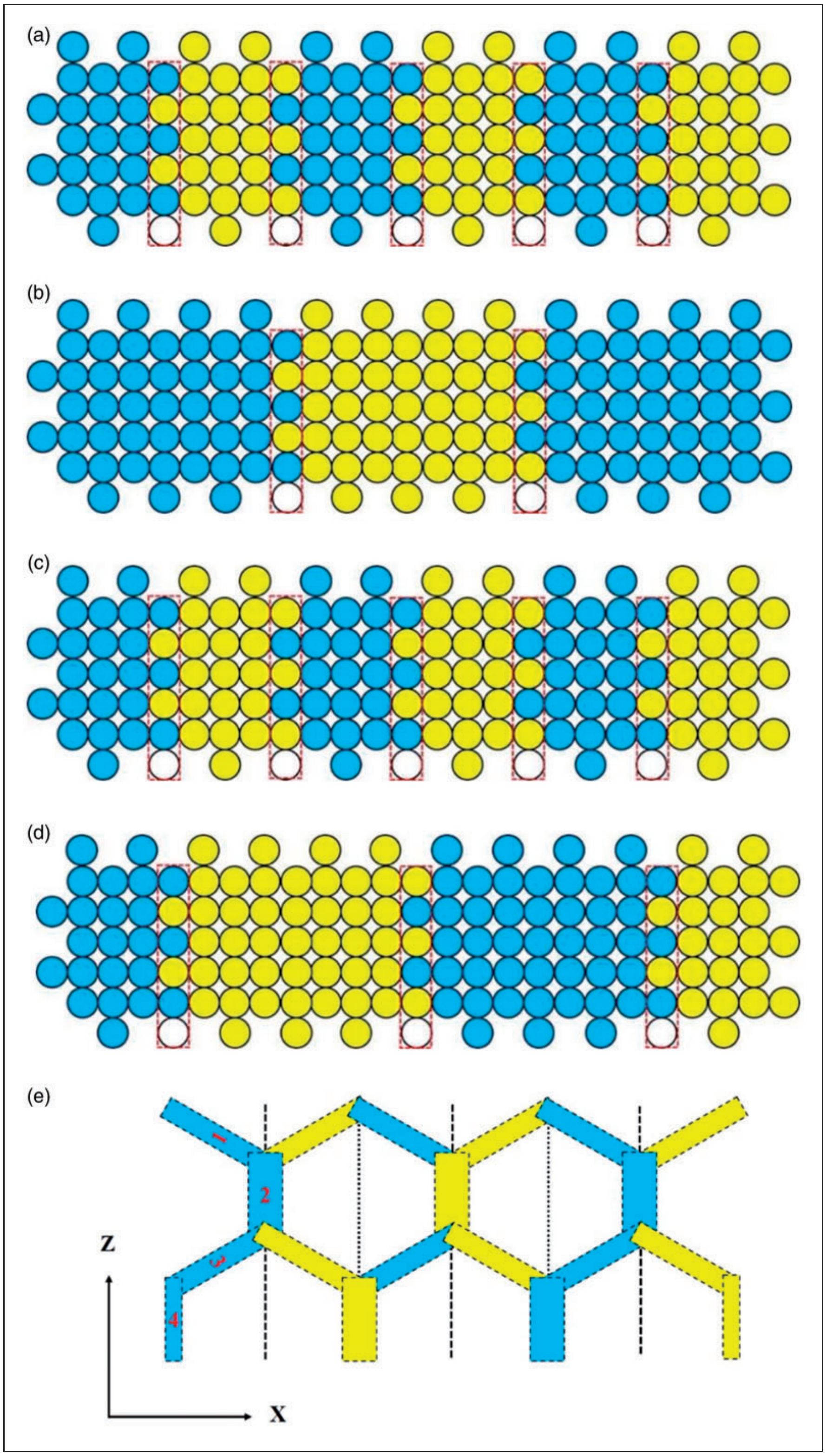


Figure 5. Schematic diagram of the yarn permutation and the braiding process of a three-dimensional (3D) braided honeycomb structure fabric with a wall thickness of three columns of yarns.

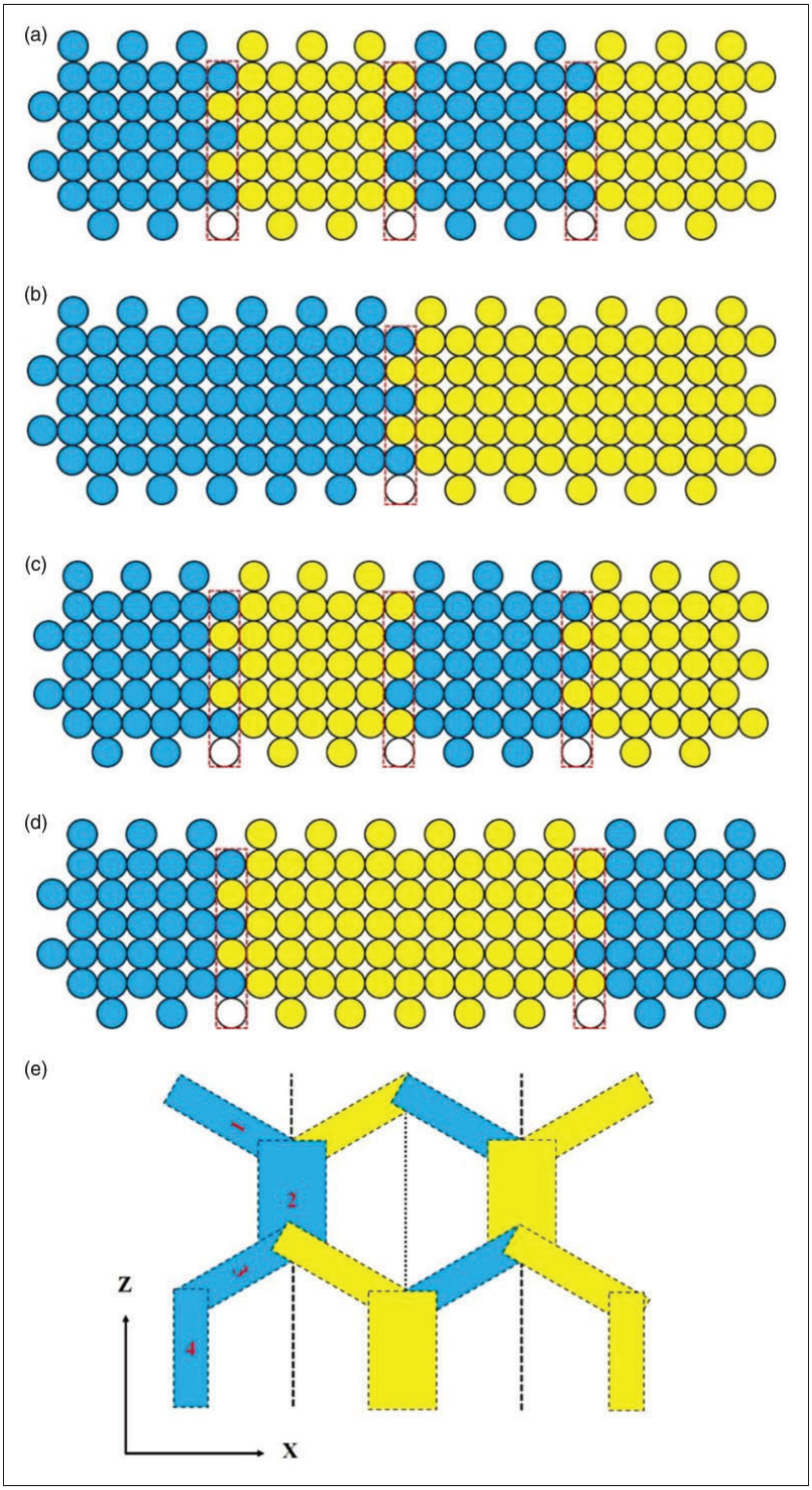


Figure 6. Schematic diagram of the yarn permutation and the braiding process of a three-dimensional (3D) braided honeycomb structure fabric with a wall thickness of five columns of yarns.

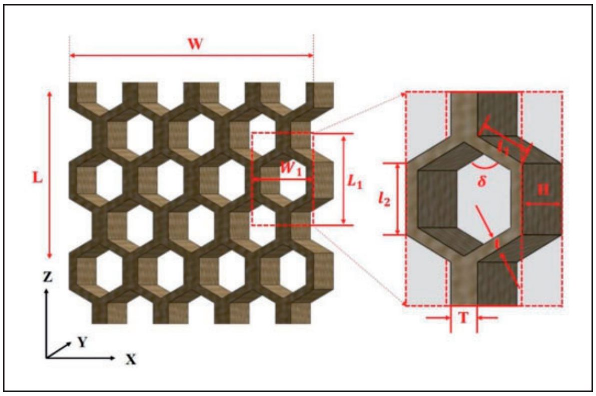


Figure 7. Schematic diagram of a honeycomb structure.

Table 1. The description of parameters

Parameter	Variable	Parameter	Variable
Width	W	The length of a cell wall	l
Height	H	The length of a free wall	l_1
Length	L	The length of a joint wall	l_2
The thickness of a free wall	t	Opening angle	δ
The thickness of a joint wall	T	The number of braiding cycles	f

According to formulas (1) and (2), the wall thickness and the height of a 3D braided honeycomb can be written as:

$$t = \frac{m_1 + \sqrt{2} - 1}{2} \cdot h \cdot \tan\alpha \tag{3}$$

$$T = \frac{m_2 + \sqrt{2} - 1}{2} \cdot h \cdot \tan\alpha \tag{4}$$

$$H = \frac{n + \sqrt{2} - 1}{2} \cdot h \cdot \tan\alpha \tag{5}$$

with $m_2 = 2m_1 + 1$, the relationship between t and T can be obtained:

$$\frac{t}{T} = \frac{m_1 + \sqrt{2} - 1}{2m_1 + \sqrt{2}} \tag{6}$$

The free wall length and the joint wall length are written as:

$$l_1 = f_1 \cdot h$$

$$l_2 = f_2 \cdot h$$

However, the fabric will be stretched when the mold is filled, and the position of yarns at the joint will be changed. Due to the inclination of the yarns at the joint, a part of the first pitch length and the last pitch length of joint wall belongs to free wall length, and the joint wall length will be reduced, as shown in Figure 9. By filling the actual fabric with a suitable mold, it can be obtained that approximately $0.8h$ will be added to the length of the free wall, and the length of the joint wall will be reduced by $1.6h$. So the free wall length and the joint wall length can be shown:

$$l_1 = (f_1 + 0.8) \cdot h \tag{7}$$

$$l_2 = (f_2 - 1.6) \cdot h \tag{8}$$

At this time, $f_2 \geq 2$. The stretched fabric is closer to a diamond-shaped fabric if $f_2 = 1$. Select one of the unit cells in Figure 7 for analysis, the expressions for the length and width of a hexagonal unit cell are shown:

$$\begin{aligned} W_1 &= \sin\frac{\delta}{2} \cdot 2l_1 + 2t \\ &= \sin\frac{\delta}{2} \cdot 2(f_1 + 0.8) \cdot h + \left(m_1 + \sqrt{2} - 1\right) \cdot h \cdot \tan\alpha \end{aligned} \tag{9}$$

$$\begin{aligned} L_1 &= 2 \times l_1 \times \cos\frac{\delta}{2} + 2l_2 \\ &= 2(f_1 + 0.8) \cdot h \cdot \cos\frac{\delta}{2} + 2(f_2 - 1.6) \cdot h \end{aligned} \tag{10}$$

The most important braiding parameters of 3D braiding are the braiding angle α and the pitch length h. Similarly, the 3D braided honeycomb structure also follows the basic principle of the 3D braided 'four-step' method during the braiding process. Therefore, the parameters t, T, and H of the 3D braided honeycomb structure are also affected by the pitch length h and the braiding angle α, while l_1, l_2, and L_1 are only affected by the pitch length h. In addition to these two parameters, the free wall thickness t is related to the number of columns m_1. The more columns of yarns involved in braiding, the thicker the wall thickness. The joint wall thickness T is related to the number of columns m_2. The height of the honeycomb H is related to the number of rows n braiding in the Y direction. The wall lengths l_1 and l_2 are not only related to the pitch length h, but also related to the number of braiding cycles f_1 and f_2. The ratio of f_1 and f_2 determines the shape of the honeycomb structure. Increasing or decreasing the number of braiding cycles f_1 and f_2 can make hexagonal cells larger or smaller.

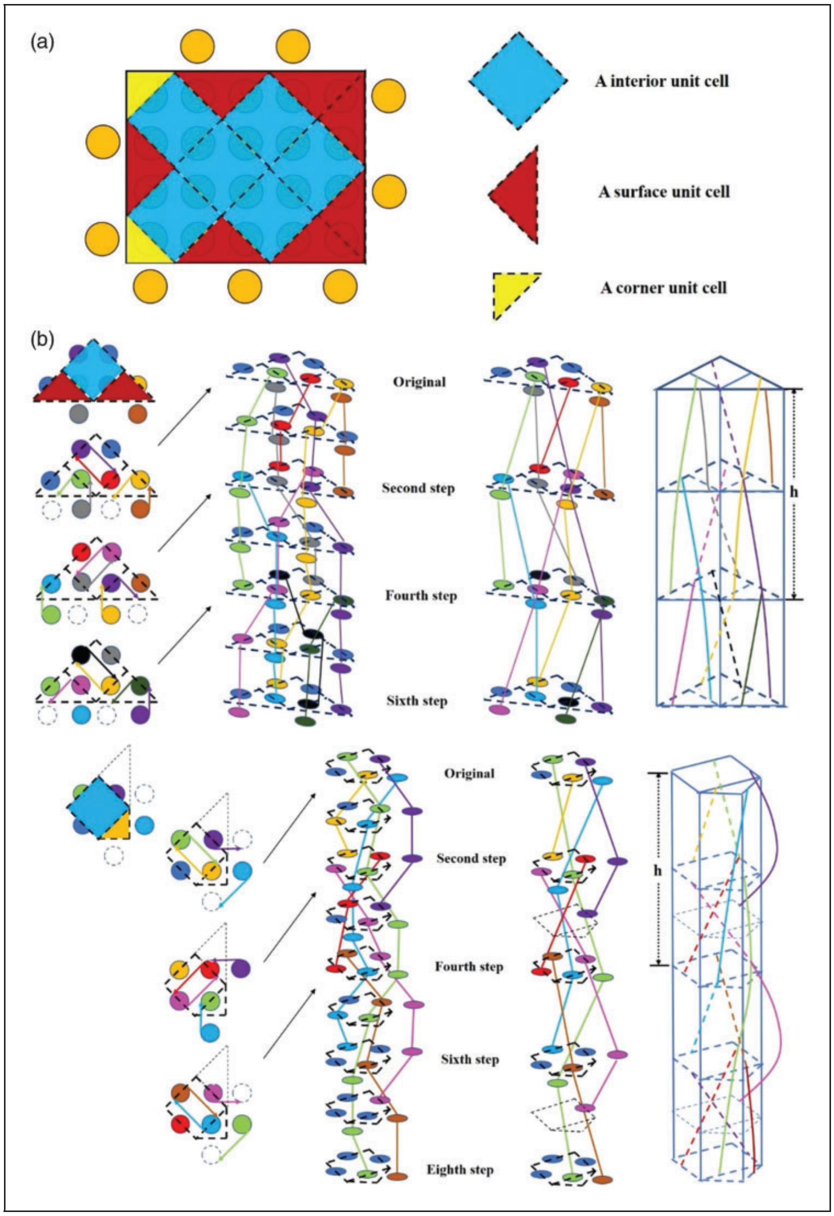


Figure 8. Schematic diagram of yarn traces and braiding parameters in three types of unit-cell models[35] (The braid is first divided into interior unit-cells, surface unit-cells, and corner unit-cells as illustrated in Figure 8(a). According to the movement of yarn carriers, connect the traces of the same yarn with straight lines using the same color, as shown in Figure 8(b). Then connect yarn traces after every braiding cycle with a smooth curve, as shown in Figure 8(c).) (a) Schematic illustration of the interior, surface and corner of a braided preform; (b) the movement process of the yarns in three unit-cell models and the formation of yarn traces and (c) the traces of yarns and braiding parameters in three types of unit-cell models.

The Z-direction is the forming direction of the honeycomb structure, and the length of a unit cell L_1 is determined by the number of braiding cycles f_1, f_2 and the opening angle δ.

It must be noted that neither the type of yarns nor yarn counts are not included in the equations (9) and (10). These parameters will not affect the geometric parameters of a 3D braided honeycomb. Irrespective of yarn type, as long as its braiding angle and pitch length can be determined, a honeycomb fabric that meets certain requirements can be designed. In addition, arguably the properties of the yarn itself can have an impact on the properties of the final composite. The size of the machine can be determined according to the size of a unit cell. If current yarns and braiding parameters are still used, as long as the number of braiding cycles of the free wall is bigger than 8, a 3D braided honeycomb fabric with a width

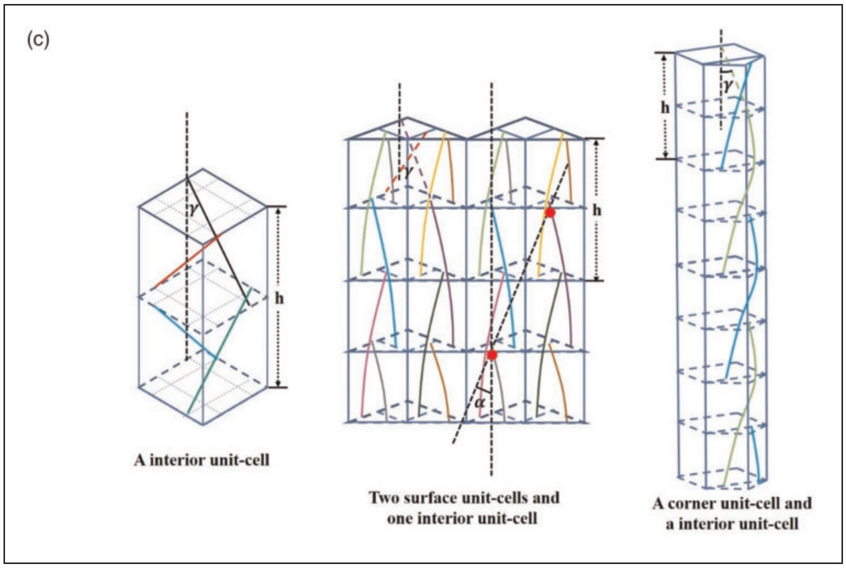


Figure 8. Continued.

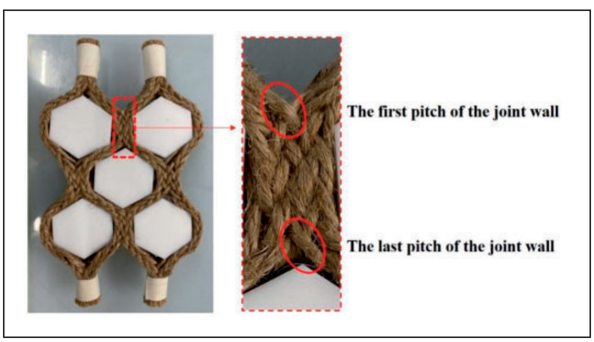


Figure 9. The fabric is stretched and filled with molds.

of more than 1 m can be realized on the current braiding machine (It has 55 (column) × 35 (row) yarn carriers.) The current samples were made in a laboratory set-up. 3D braiding at industrial scale has the potential to manufacture 3D braided honeycomb fabric of several square meters.

2.2 Analysis of honeycomb structure parameters

The response of the honeycomb structure to static and dynamic loads depends on design parameters, namely relative density, cell orientation, cell wall thickness, wall length, and cell size. Among these parameters, the relative density is one of the most important parameters to determine the performance of honeycomb structures under static and dynamic conditions.[39,40] The relative density of the honeycomb structure is the percentage of the solid volume of the honeycomb structure to the volume of the entire honeycomb cuboid structure.[40] These two volumes have the same height, so only the surface area is considered. Combining the unit cell geometry shown in Figure 7 and formulas (9) and (10), the surface area of the honeycomb structure and the surface area of the cuboid occupied by the honeycomb structure can be obtained according to the following formulas:

$$S = W_1 \cdot L_1 = \left(\sin\frac{\delta}{2} \cdot 2l_1 + 2t\right) \cdot \left(2l_2 + 2l_1 \cdot \cos\frac{\delta}{2}\right)$$

$$S_1 = 4l_1 \cdot t + 2l_2 \cdot t + l_2 \cdot T$$

The relative density is therefore given by

$$\mu = \frac{S_1}{S} = \frac{4l_1 \cdot t + 2l_2 \cdot t + l_2 \cdot \mathrm{T}}{\left(\sin\frac{\delta}{2} \cdot 2l_1 + 2t\right) \cdot \left(2l_2 + 2l_1 \cdot \cos\frac{\delta}{2}\right)} \tag{11}$$

It can be seen from formula (6) that $T = \frac{(2m_1+\sqrt{2})\cdot t}{m_1+\sqrt{2}-1}$, so formula (11) can be simplified to

$$\begin{aligned}\mu = \frac{S_1}{S} &= \frac{4l_1 \cdot t + 2l_2 \cdot t + l_2 \cdot \mathrm{t} \cdot \frac{(2m_1+\sqrt{2})}{m_1+\sqrt{2}-1}}{\left(\sin\frac{\delta}{2} \cdot 2l_1 + 2t\right) \cdot \left(2l_2 + 2l_1 \cdot \cos\frac{\delta}{2}\right)} \\ &= \frac{\frac{l_1}{t} + \frac{l_2}{2t} + \frac{l_2}{4t} \cdot \frac{2m_1+\sqrt{2}}{m_1+\sqrt{2}-1}}{\left(\sin\frac{\delta}{2} \cdot \frac{l_1}{t} + 1\right) \cdot \left(\frac{l_2}{t} + \frac{l_1}{t} \cdot \cos\frac{\delta}{2}\right)}\end{aligned} \tag{12}$$

It can be seen that the relative density of the honeycomb structure is affected by the opening angle δ and $\frac{l_1}{t}$ and $\frac{l_2}{t}$. From formulas (3), (7), and (8), it can be shown that $\frac{l_1}{t}$ and $\frac{l_2}{t}$ can be represented by braiding parameters, as shown below

$$\frac{l_1}{t}=\frac{2(f_1+0.8)}{\left(m_1+\sqrt{2}-1\right)\cdot\tan\alpha},\ \frac{l_2}{t}=\frac{2(f_2-1.6)}{\left(m_1+\sqrt{2}-1\right)\cdot\tan\alpha},$$

The relative density μ of a 3D braided honeycomb structure is therefore related to f_1, f_2, m_1, α, and δ. The effects of braiding parameters and structural parameters on relative density are shown in Figure 10.

When m_1, α, and δ are constant values, f_2 does not change; with the increase of braiding cycles f_1, the relative density will gradually decrease. When f_1 is constant, the relative density will also gradually decrease with the increase of braiding cycles f_2, as shown in Figure 10(a). However, the relative density decreased more strongly with f_1, so, the effect of the braiding cycles f_1 on the relative density is greater. Similarly, when f_1, f_2, α, and δ are constant, the relative density gradually increases with the increase of the number of columns m_1 forming the free wall thickness, as illustrated in Figure 10(b). However, when other parameters remain unchanged, the relative density will show an approximately linear increase with the increase of the braiding angle α, as shown in Figure 10(c), and the relative density gradually decreases with the increase of the opening angle δ, although there is a minimum point after which a little increase is observed, as shown in Figure 10(d).

2.3 Experimental validation of the theoretical model

To verify the rationality of the above derivation, parametric tests were carried out on 3D braided honeycomb composites. Three-dimensional braided honeycomb fabrics with different joint walls were braided. Every sample has the same number of braiding cycles, but the number and size of cells are different because of varying joint wall lengths, as shown in Figure 11(a). The same fabrics were filled with different molds to form honeycomb fabrics with different opening angles, as shown in Figure 11(b).

The trend of the predicted value and the actual value is consistent, as illustrated in Figure 12. However, the

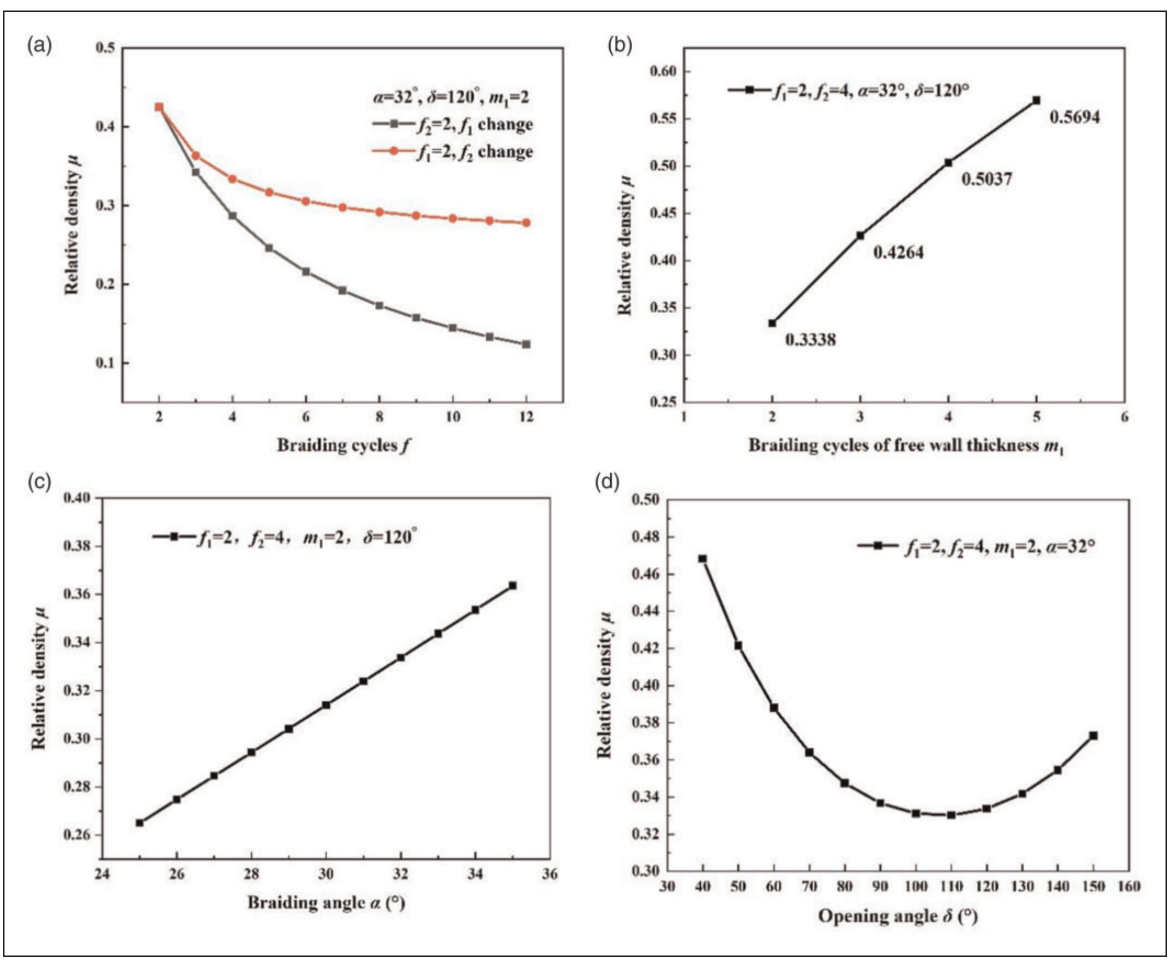


Figure 10. The effects of braiding parameters and structural parameters on relative density.

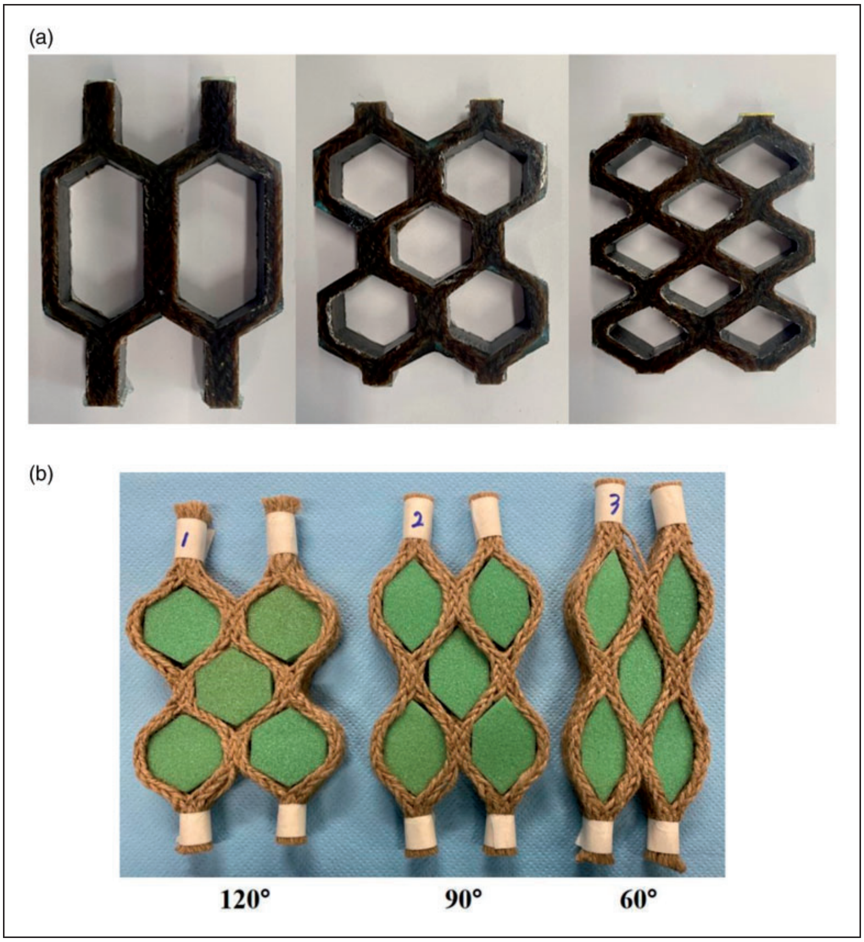


Figure 11. Real three-dimensional (3D) braided honeycomb composite and honeycomb fabric. (a) 3D braided honeycomb composite with different joint lengths in the same braiding cycles and (b) 3D braided honeycomb fabrics with different opening angles.

trends of measured values are bigger than predicted values. This is because, in the process of calculation derivation, it is assumed that the pitch length and the braiding angle are uniform and do not change. In the actual fabrication process of the composite honeycomb, however, the pitch length and the braiding angle will be affected by the hexagonal mold that is filled in the fabric. The more molds that are filled, the more significantly the pitch length will be stretched, then the solid volume of honeycomb will be larger, so the measured values of the relative density are bigger than theoretically calculated values.

However, as the number of braiding cycles of the joint wall decreases and the opening angle increases, the error will become smaller and smaller. This is because the reduction of joint wall length increases the number of molds, the fabric will be squeezed tighter, and the resin-rich area will be reduced. Similarly, when the number of molds is the same, the bigger the opening angle of the molds, the larger the area of the molds, and the tighter the fabric is squeezed. Then the gap between the molds and the fabric is smaller, and there will be fewer resin-enriched areas. The standard deviation is within the error range and the above derivation can be considered reasonable. Therefore, different honeycomb fabrics can be designed using the relationship between braiding parameters and structural parameters.

It can be seen from Figure 10 and Figure 12 that the relative density of the 3D braided honeycomb structure is above 0.26. However, commercially available honeycombs usually have a low relative density, for example, commercial aluminum honeycombs are usually less than 0.05.[41] The relative density of the braided honeycomb structures is high, particularly larger than traditional honeycomb structures (aluminum honeycomb and paper honeycomb), which makes them not attractive to many applications in its current state. However, the research is not to develop a concept for specific applications, but to understand how different geometrical parameters within honeycomb structure including its braiding architecture relate to the overall

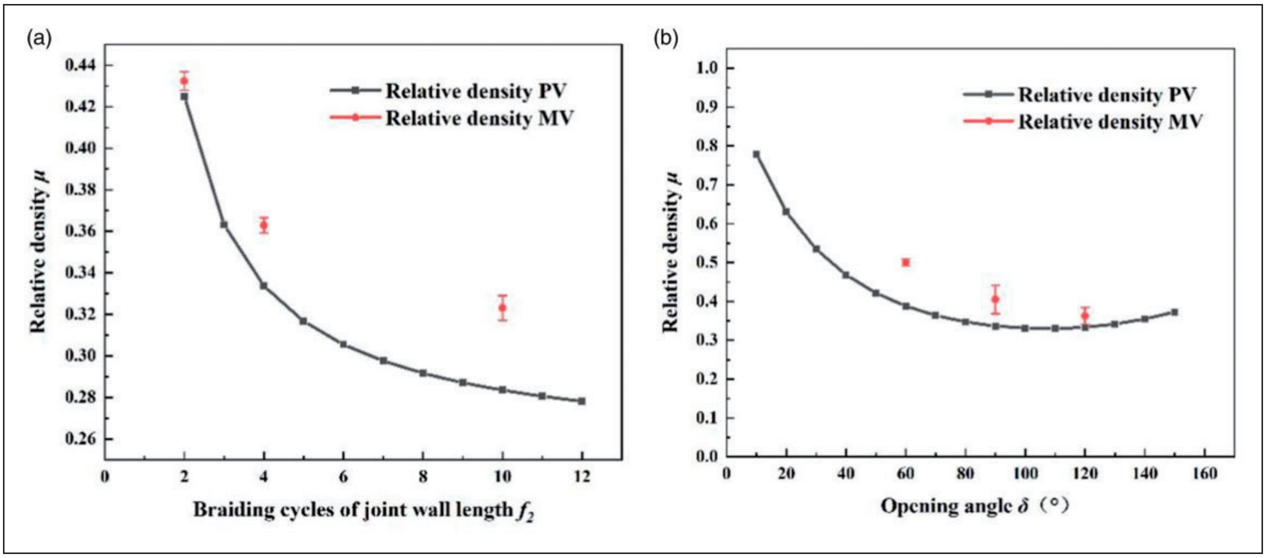
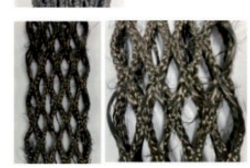


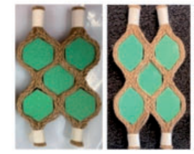
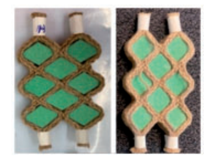
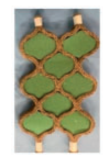
Figure 12. The comparison between the predicted values and measured values. (a) The relative density as a function of f_2 ($m_1 = 2$, $\alpha = 32°$, $\delta = 120°$, $f_1 = 2$) and (b) The relative density as a function of δ ($m_1 = 2$, $\alpha = 32°$, $f_1 = 2$, $f_2 = 4$).

Table 2. Three-dimensional braided honeycomb fabrics with different cell shapes and kinds of yarns.

Sample	m_1	f_1	f_2	Material	Honeycomb fabric
(a)	2	4	4	Polyester yarns with the diameter of 2 mm	
(b)	2	2	1	Polypropylene yarns with the diameter of 2 mm	
(c)	3	2	1		
(d)	2	2	2	12K carbon fibers	
(e)	2	0	4		

(continued)

Table 2. Continued.

Sample	m_1	f_1	f_2	Material	Honeycomb fabric
(f)	2	2	4		
(g)	2	2	10	Jute yarns with diameter of 2 mm	
(h)	2	2	2		
(i)	2	4	4		

performance. Once this relationship is fully understood, honeycomb structures for certain applications can be designed. In the meantime, the relative density can be changed by changing the diameter of yarns and the length of joint wall and free wall. The self-made 3D braiding machine for the research is the most suitable for braiding 2 mm yarns. Once this technology is further developed and established, new 3D braiding machines could be developed that can handle smaller-diameter yarns.

3. Fiber trade-off for 3D braided honeycomb

The shape of 3D braided honeycomb is easily changed in the fabrication process so that m_1, m_2, f_1, f_2 should be determined and kept constant, and the braiding angle α and the pitch length h also become constant values during the braiding process. When the braiding is completed, it is assumed that the braiding angle α and the pitch length h do not change under the composite manufacturing. Then, m_1, m_2, f_1, f_2, and n are all constant values, combined with formulas (9) and (10) and it can be known that W_1 and L_1 are only affected by the opening angle δ. The value of the opening angle δ is $0^\circ \leq \delta < 180^\circ$. When $\delta = 0^\circ$, the fabric is not stretched. When $\delta = 180^\circ$, the shape of fabric becomes a rectangle. In fact, the fabric will not be stretched into a rectangle due to the restriction of yarns interlacing. Different shapes of 3D braided honeycomb fabrics were braided with different kinds of yarns, as shown in Table 2.

Material selection is a key factor in the design and development of new structures. To determine the feasibility of the material, different types of yarns were used for braiding. Polyester yarns and polypropylene yarns are twisted strands; the yarn carrier will rotate with the yarns untwisting during the braiding process. Then the carrier falling off the machine will disturb the braiding process. However, the fabrics formed are smooth and less filoplume. For carbon fiber, it will be fluffed after beating up, and will be seriously damaged, so the advantages of its performance cannot be fully utilized. When the honeycomb fabric is braided with jute yarns, the yarn carriers are rarely dropped from the machine as they hardly rotate with the movement of jute yarns. However, the hairiness of jute is seriously scattered, and falling on the machine will cause the movement of yarn carriers to be stuck, which needs to be cleaned up in time. However, the braiding process is relatively successful in comparison. By braiding different shapes of honeycomb fabrics with different kinds of yarns, it can be found that using jute yarns for 3D braided honeycomb fabrics offers significant cost advantages and benefits associated with processing. Jute not only makes the braiding process smooth, but also conforms to today's concept of green environmental protection and sustainable development compared with synthetic fibers.

4. Conclusion

The 3D braided honeycomb fabric is realized using the basic principle of the 3D braiding 'four-step' method. By controlling the regular movement of yarn carriers, the interlaced state of yarns can be changed. Then the separating and combination of the braid can be controlled. Hence, 3D braided honeycomb fabrics can be manufactured using the principles outlined in this paper.

The relationship between braiding parameters and honeycomb geometric parameters has been established. The reduction of the relative density of the 3D braided honeycomb structure can be achieved by increasing the number of braiding cycles of the wall length, or by reducing the number of yarn columns involved in braiding wall thickness. Reducing the braiding angle also reduces relative density. As the opening angle increases, the relative density gradually decreases, and there is a slight increase after a minimum point. The relative density can also be changed by changing the diameter of yarns. Irrespective of yarn types, as long as its braiding angle and pitch length can be known, a honeycomb fabric that meets certain requirements can be designed and the relative density of the formed honeycomb composite can be estimated. Different cell sizes and shapes can be braided with natural fibers. Combined with different kinds of resin matrix, it is expected to realize a green, sustainable, and functional honeycomb structure.

This paper illustrates how to design and develop 3D braided honeycomb fabrics in different shapes and configurations, and provides significant guidance for designing various 3D braided honeycomb structures. The relationship between geometric parameters and performance of 3D braided honeycomb composites will be explored in future work. Based on a complete understanding of the composite's performance, 3D braided honeycomb fabrics with different architectures can be designed, tailored, and optimized for a specific application.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iDs

Qianqian Li https://orcid.org/0000-0001-9580-931X
Wei Li https://orcid.org/0000-0002-1561-166X

References

1. Farooq U, Ahmad MS, Rakha SA, et al. Interfacial mechanical performance of composite honeycomb sandwich panels for aerospace applications. *Arab J Sci Engng* 2016; 42: 1775–1782. DOI: 10.1007/s13369-016-2307-z.
2. Ganilova OA, Cartmell MP and Kiley A. Experimental investigation of the thermoelastic performance of an aerospace aluminium honeycomb composite panel. *Comp Structs* 2021; 257(113159). DOI: 10.1016/j.compstruct.2020.113159.
3. Kececi E and Asmatulu R. Effects of moisture ingressions on mechanical properties of honeycomb-structured fiber composites for aerospace applications. *Int J Advd Mfg Technol* 2016; 88: 459–470. DOI: 10.1007/s00170-016-8744-8.
4. Saseendran V and Berggreen C. Mixed-mode fracture evaluation of aerospace grade honeycomb core sandwich specimens using the double cantilever beam–uneven bending moment test method. *J Sandwich Struct Mater* 2018; 22(4): 991–1018. DOI: 10.1177/1099636218777964.
5. Du J, Hao P, Liu M, et al. Energy absorbed ability and damage analysis for honeycomb sandwich material of bio-inspired micro aerial vehicle under low velocity impact. *Proceedings IMechE. Part C: J Mech Engng Sci* 2020. DOI: 10.1177/0954406220975427.
6. Wang J, Shi C, Yang N, et al. Strength, stiffness, and panel peeling strength of carbon fiber-reinforced composite sandwich structures with aluminum honeycomb cores for vehicle body. *Comp Structs* 2018; 184: 1189–1196. DOI: 10.1016/j.compstruct.2017.10.038.
7. Xiao Y, Hu Y, Zhang J, et al. The bending responses of sandwich panels with aluminium honeycomb core and CFRP skins used in electric vehicle body. *Adv Mater Sci Engng* 2018; 2018: 1–11. DOI: 10.1155/2018/5750607.
8. Palomba G, Epasto G, Sutherland L, et al. Aluminium honeycomb sandwich as a design alternative for lightweight marine structures. *Ships Offshore Structs* 2021: 1–12. DOI: 10.1080/17445302.2021.1996109.
9. Baral N, Cartié DDR, Partridge IK, et al. Improved impact performance of marine sandwich panels using through-thickness reinforcement: Experimental results. *Compos Part B: Engng* 2010; 41: 117–123. DOI: 10.1016/j.compositesb.2009.12.002.
10. Wang Z. Recent advances in novel metallic honeycomb structure. *Compos Part B: Engng* 2019; 166: 731–741. DOI: 10.1016/j.compositesb.2019.02.011.
11. Tripathi L and Behera BK. Review: 3D woven honeycomb composites. *J Mater Sci* 2021; 56: 15609–15652. DOI: 10.1007/s10853-021-06302-5.
12. Wei X, Xiong J, Wang J, et al. New advances in fiber-reinforced composite honeycomb materials. *Sci China Technol Sci* 2020; 63(8): 1348–1370. DOI: 10.1007/s11431-020-1650-9.
13. Xiong J, Zhang M, Stocchi A, et al. Mechanical behaviors of carbon fiber composite sandwich columns with three dimensional honeycomb cores under in-plane compression. *Compos Part B: Engng* 2014; 60: 350–358. DOI: 10.1016/j.compositesb.2013.12.049.

14. Zhang Q, Yang X, Li P, et al. Bioinspired engineering of honeycomb structure – using nature to inspire human innovation. *Prog Mater Sci* 2015; 74: 332–400. DOI: 10.1016/j.pmatsci.2015.05.001.
15. Khan MK, Baig T and Mirza S. Experimental investigation of in-plane and out-of-plane crushing of aluminum honeycomb. *Mater Sci Engng: A* 2012; 539: 135–142. DOI: 10.1016/j.msea.2012.01.070.
16. Mozafari H, Molatefi H, Crupi V, et al. In plane compressive response and crushing of foam filled aluminum honeycombs. *J Compos Mater* 2014; 49(26): 3215–3228. DOI: 10.1177/0021998314561069.
17. Ahmad S, Zhang J, Feng P, et al. Processing technologies for Nomex honeycomb composites (NHCs): A critical review. *Compos Struct* 2020; 250. DOI: 10.1016/j.compstruct.2020.112545.
18. Xie S, Jing K, Zhou H, et al. Mechanical properties of Nomex honeycomb sandwich panels under dynamic impact. *Compos Struct* 2020; 235. DOI: 10.1016/j.compstruct.2019.111814.
19. Prabhakaran S, Krishnaraj V, Shankar K, et al. Experimental investigation on impact, sound, and vibration response of natural-based composite sandwich made of flax and agglomerated cork. *J Compos Mater* 2019; 54(5): 669–680. DOI: 10.1177/0021998319871354.
20. Vitale JP, Francucci G, Xiong J, et al. Failure mode maps of natural and synthetic fiber reinforced composite sandwich panels. *Compos Part A: Appl Sci Mfg* 2017; 94: 217–225. DOI: 10.1016/j.compositesa.2016.12.021.
21. Stocchi A, Colabella L, Cisilino A, et al. Manufacturing and testing of a sandwich panel honeycomb core reinforced with natural-fiber fabrics. *Mater Des*2014; 55: 394–403. DOI: 10.1016/j.matdes.2013.09.054.
22. Petrone G, Rao S, De Rosa S, et al. Initial experimental investigations on natural fibre reinforced honeycomb core panels. *Composites Part B: Engineering* 2013; 55: 400–406. DOI: 10.1016/j.compositesb.2013.06.047.
23. Pehlivan L and Baykasoğlu C. An experimental study on the compressive response of CFRP honeycombs with various cell configurations. *Compos Part B: Engng* 2019; 162: 653–661. DOI: 10.1016/j.compositesb.2019.01.044.
24. Dongyup, Han, Tsai, et al. Interlocked composite grids design and manufacturing. *J Comp Mater* 2003; 37(4):287–316.
25. Compton BG and Lewis JA. 3D-printing of lightweight cellular composites. *Adv Mater* 2015; 26(34): 5930–5935.
26. Wei X, Li D and Xiong J. Fabrication and mechanical behaviors of an all-composite sandwich structure with a hexagon honeycomb core based on the tailor-folding approach. *Comp Sci Technol* 2019; 184. DOI: 10.1016/j.compscitech.2019.107878.
27. Kamble Z, Mishra RK, Behera BK, et al. Design, development, and characterization of advanced textile structural hollow composites. *Polymers (Basel)* 2021;13(20):3535. 2021/10/24. DOI: 10.3390/polym13203535.
28. Xiao X, Hua T, Li L, et al. Geometrical modeling of honeycomb woven fabric architecture. *Text Res J* 2015; 85(16): 1651–1665. DOI: 10.1177/0040517514548754.
29. 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* 2008; 78(9): 771–781. DOI: 10.1177/0040517507087855.
30. Chen X, Sun Y and Gong X. Design, manufacture, and experimental analysis of 3D honeycomb textile composites. Part II: EXPERIMENTAL ANALYSIS. *Text Res J* 2008; 78(11): 1011–1021. DOI: 10.1177/0040517507087683.
31. Tripathi L, Neje G and Behera BK. Geometrical modeling of 3D woven honeycomb fabric for manufacturing of lightweight sandwich composite material. *J Ind Text* 2022; 51(3S): 4372S–4389S. DOI: 10.1177/1528083720931472.
32. Antony S, Cherouatl A and Montay G. Hemp fibre woven fabrics/polypropylene based honeycomb sandwich structure for aerospace applications *Adv Aircraft Spacecraft Sci* 2019; 6(2): 87–103. DOI: 10.12989/aas.2019.6.2.087.
33. Gu Q, Quan Z, Yu J, et al. Structural modeling and mechanical characterizing of three-dimensional four-step braided composites: A review. *Comp Structs* 2019; 207: 119–128. DOI: 10.1016/j.compstruct.2018.09.065.
34. Ouyang Y and Wu X. A review on the mechanical properties of textile structural composite T-beams. *Text Res J* 2019; 90(5-6): 710–727. DOI: 10.1177/0040517519871259.
35. Chen L, Tao X and Choy C. On the microstructure of three-dimensional braided performs. *Compos Sci Technol* 1999; 59(3): 391–404.
36. Wang Y Q WA. On the topological yarn structure of 3-D rectangular and tubular braided preforms *Compos Sci Technol* 1994; 51(4):575–586.
37. Li D-S, Li C and Li J-l. Microstructure and unit-cell geometry of four-step three-dimensional rectangular braided composites. *Reinf Plastics Compos* 2010; 29: 3353–3363. DOI: 10.1177/0731684410369022.
38. Jiang J, Wen Z, Wu B, et al. The design of a three-dimensional honeycombed braiding. *Technical Textiles* 2009; 4 (4): 1–16. DOI:10.3969/j.issn.1004-7093.2009.04.004
39. Alkhader M, Iyer S, Shi W, et al. Low frequency acoustic characteristics of periodic honeycomb cellular cores: The effect of relative density and strain fields. *Compos Structs* 2015; 133: 77–84. DOI: 10.1016/j.compstruct.2015.07.102.
40. Wang A. Yield surfaces of various periodic metal honeycombs at intermediate relative density. *Int J Plasticity* 2005; 21: 285–320. DOI: 10.1016/j.ijplas.2003.12.002.
41. Balawi S and Abot JL. The effect of honeycomb relative density on its effective in-plane elastic moduli: An experimental study. *Compos Structs* 2008; 84(4): 293–299. DOI: 10.1016/j.compstruct.2007.08.009.