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Reinforcement structure design and matrix model establishment of tubular 3D weaving based on ordinary loom

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Abstract

In order to optimize the design of three-dimensional tubular woven (3DTW), a design method and matrix model of 3DTW were proposed based on normal loom, where 3D woven was used as tube wall and the weaving method of tubular fabric was applied. Herein, 3D woven was used as the tube wall to obtain the face weave diagram, and the back weave diagram was subsequently obtained by the "negative flip" method. According to the method of layering weaving, the structure diagram of 3DTW could be determined. In order to obtain back weave matrix, the elements in the face weave matrix were replaced and reordered by MATLAB function, and Kronecker product operation was used to achieve the proportional embedding of the face and the back weave matrix and the assignment of the face warp by lifting point elements when weaving the back weft. Finally, the weave matrix of 3DTW was obtained. The proposed design method and matrix model can improve the design efficiency and reduce weaving cost of 3DTW, which could provide a reference for the design and preparation of 3DTW.

Keywords: 3D tubular woven, Weave diagram, Interlacing rule, Weave matrix, Kronecker product

Introduction

Fiber reinforced tubular structure have attracted more and more attention in recent years due to their high specific stiffness and strength, especially for three-dimensional (3D) fabrics reinforced preforms, which possesses specific features of excellent impact resistance and outstanding corrosion resistance compared with traditional laminated composites (Liu et al., 2023; Qiao et al., 2023; Zheng et al., 2022). In particular, they overcome the poor interlayer performance of the traditional laminates, realizes the integral forming of the components, and have been widely used as reinforcements in composite applications (Perera et al., 2021). Meanwhile, tubular structure is greatly applicated in various areas such as aerospace (Rajak et al., 2022), construction (Dagher et al., 2012; Wang and Li, 2023), medicine (Wang et al., 2023a) and other fields by now. Therefore, the design and mechanical properties investigation of 3D tubular fabric reinforced composites have important application value in various areas in future.

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By now, some researches have been conducted on tubular 3D fabrics and related composites. A novel 3D fully integrated multilayer tubular fabric was developed to avoid the delamination issue and investigated relevant compression behaviors (Zhang et al., 2019). It was revealed that the type of winding yarn could obviously influence the axial compressive strength. Mechanical properties of braided fabric reinforced tubular structures was predicted by machine learning method (Wenhao Wang et al., 2021). The compressive behavior and failure modes of 3D braided tubular composites was analyzed based on a novel unit cell by finite element analysis, where a geometric modeling method was established to integrate the inner and outer surface elements of tubular composites into a single unit cell, and the parameters were parameterized (Li et al., 2022).

However, most of investigations are mainly focused on 3D tubular braided fabrics reinforced composites, while the studies on 3D tubular woven (3DTW) fabrics reinforced composites are limited (Leung et al., 2013). The geometric model of 3DTW fabric was established based on the minimal repeating structural unit, which provided a theoretical basis for the calculation of fiber volume fraction, voids distribution and mechanical prediction of tubular composite (Wei Wang et al., 2017). Axial-compression properties of 3DTW composite was researched by experiment and finite element analysis, and found that both the number of layers and the inner diameter significantly affected the axial-compression properties (Zhu et al., 2020). With the increase of inner diameter and layer numbers, both peak load and energy absorption of tubular woven composites clearly increased. 3D woven tubular composites (3D-WTC) with a "double tube and double ribs" concentric circular nested biomimetic structures showed excellent mechanical properties and the specific energy absorption could reach 7.74 $J\cdot g^{-1}$ (Wen et al., 2024).

Finite element analysis has become an important method to predict the mechanical properties and study the failure mechanism of fabric-reinforced composites (B. Wang et al., 2022; Zhou et al., 2015). Meanwhile, the accurate structural modeling is very important for accurate prediction of composite properties and failure mechanism. Compared to specialized 3D weaving equipment, using a normal loom for weaving can not only provides design flexibility but also reduces weaving costs (Chen et al., 2016; Guo, 2015). However, the design of tissue chart and structural modeling are an important step in weaving tubular 3D woven fabric based on flat loom. By now, the reported researches on 3D woven fabric model based on flat loom are limited.

Meanwhile, the traditional design method was usually based on manual drawing. Firstly, the back weave diagram is obtained based on the face weave diagram, and then according to the principle of layered weaving, the 3DTW weave diagram is correspondingly obtained. The disadvantages of this traditional method were that once the different fabric structure was selected for the face weave, the entire design must be redrawn, which is not only inefficient but also prone to errors.

However, the method proposed in this article maps the weave diagram to a matrix model, and through matrix operations, a weave matrix of the 3DTW based on the face weave matrix could be quickly generated, and correspondingly achieve program drawing, which could further improve design efficiency. Under this situation, when using face weave with different structure, it is also possible to quickly generate weave matrix of the 3DTW.

In this paper, the matrix model of 3DTW fabric structure based on a normal loom are proposed, and the design method provided in detail. In order to obtain weave matrix of 3DTW, MATLAB function and Kronecker product operation were applied. The relevant method can provide the optimize design efficiency and low-cost weaving of this kind of fabric.

Methods

Construction principle of 3DTW fabric structure

Ordinary tubular fabric is formed by using a single layer of fabric as the tube wall following the principle of layered weaving. For example, Fig. 1 shows a tubular fabric formed with plain weave as the tube wall. When weaving this tubular structure on the normal loom, we can adopt a layered weaving method of double-layer structure, which involves embedding the face and back weaves with 1:1 ratio to form a weave diagram of the tubular fabric.

The following introduces the design process of a regular tubular weave diagram with a single layer plain weave as the tube wall. Taking Fig. 1 as an example, assuming that the total number of warp yarns of the tubular fabric is 20 and the total number of weft yarns of the tubular fabric is also 20, then face weave warp and weft yarns are 10 and 10 respectively, and the back weave warp and weft yarns are 10 and 10 respectively. Draw a plain weave face weave diagram and back weave diagram, respectively. Figure 2 shows the design process of a tubular weave diagram. In order to distinguish between face and back, the icon of weave diagram is marked as follows. The warp points (at the intersection of warp and weft, the warp is above the weft) of the face weave diagram and the back weave diagram are marked with "■" and " × ", respectively. The weft points (at the intersection of warp and weft, the weft is above the warp) of both the face and the back are marked with "□". The warp yarns and weft yarns of the face weave are represented by "1" to "10" and "A" to "J", respectively. The warp yarns and weft yarns of the back weave are represented by "①" to "⑩" and "a" to "j", respectively (Wang et al., 2023b). In order to ensure that the entire outer surface of the tubular fabric is the same weave, the back and face weave should have a negative flip relationship. The figure shows the insertion of face warp yarns and back warp yarns, with both face weft yarns and back weft yarns embedded in a ratio of 1:1. Considering the principle of layered weaving, the face warp needs to be raised when weaving the back weft, that is to say, at the intersection of back

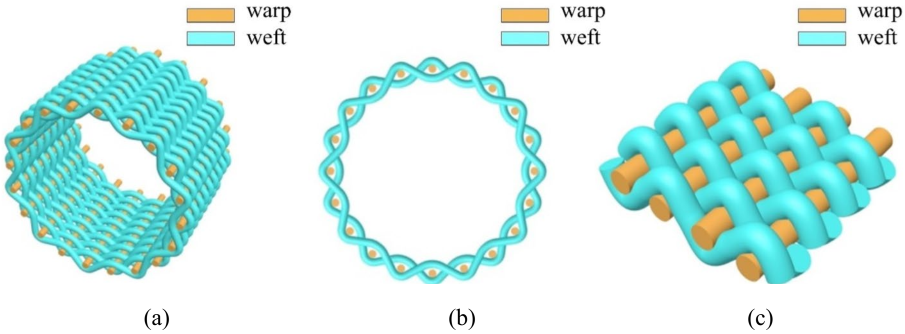
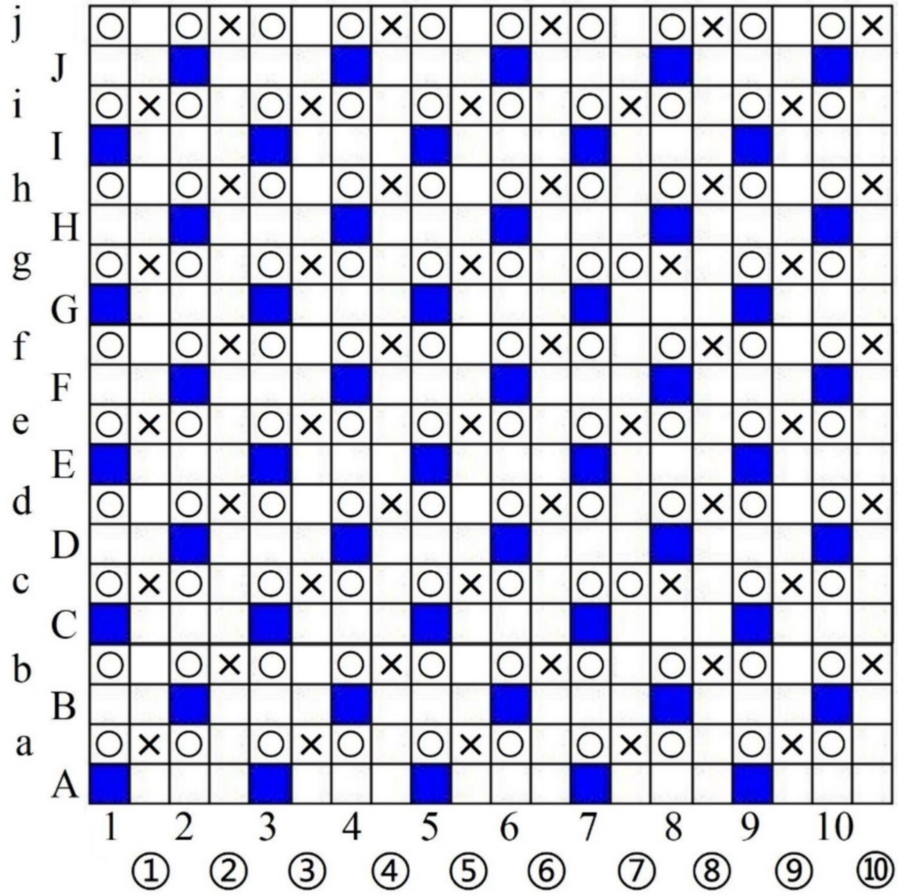


Fig. 1 Schematic diagram of tubular fabric based on plain weave from (**a**) perspective view, (**b**) cross-section view, and (**c**) plain weave as tube wall



j	○		○	×	○		○	×	○		○	×	○		○	×	○		○	×
J			■				■				■				■				■	
i	○	×	○		○	×	○		○	×	○		○	×	○		○	×	○	
I	■				■				■				■				■			
h	○		○	×	○		○	×	○		○	×	○		○	×	○		○	×
H			■				■				■				■				■	
g	○	×	○		○	×	○		○	×	○		○	○	×		○	×	○	
G	■				■				■				■				■			
f	○		○	×	○		○	×	○		○	×	○		○	×	○		○	×
F			■				■				■				■				■	
e	○	×	○		○	×	○		○	×	○		○	×	○		○	×	○	
E	■				■				■				■				■			
d	○		○	×	○		○	×	○		○	×	○		○	×	○		○	×
D			■				■				■				■				■	
c	○	×	○		○	×	○		○	×	○		○	○	×		○	×	○	
C	■				■				■				■				■			
b	○		○	×	○		○	×	○		○	×	○		○	×	○		○	×
B			■				■				■				■				■	
a	○	×	○		○	×	○		○	×	○		○	×	○		○	×	○	
A	■				■				■				■				■			
	1	①	2	②	3	③	4	④	5	⑤	6	⑥	7	⑦	8	⑧	9	⑨	10	⑩

Fig. 2 Weave diagram of tubular fabric based on plain weave

weft yarns and face warp yarns, all face warp yarns are set to warp points. To distinguish, these warp points here are marked with "○". For example, when weaving the back weft "a", the intersection of the face warp and the back weft is raised completely.

3DTW is formed with 3D woven fabric as the tube wall. Considering reducing weaving costs, using a normal loom to weave 3DTW is a good choice. It is woven using the "flattening-weaving and reducing tubular shape" method on the normal loom (Sun et al., 2014). Two layers of 3D fabric are woven and then it is reduced to form a tubular cross-section after weaving. The circumference of the tubular fabric is generally about twice the width of the fabric, and the thickness of the tube wall depends on the number of layers. The key to the effective preparation of tubular fabric lies in the design of the weave diagram, which can be divided into following three steps. Firstly, select the type of 3D woven fabric and determine the face weave diagram, which include orthogonal, angle interlock or stitching multi-layer 3D woven fabric. Secondly, the back weave diagram is obtained according to the "negative flip" method on face weave diagram. Finally, according to the weaving method on multi-layer woven, on the basis of the known face, back warp and face, back weft arrangement ratio, draw the weave diagram of 3DTW fabric. In general, for the integrated 3DTW fabric, the total number of warp yarns in fabric should be an integer multiple of the number of warp yarns in a unit cell.

Results and Discussion

Design of 3DTW fabric

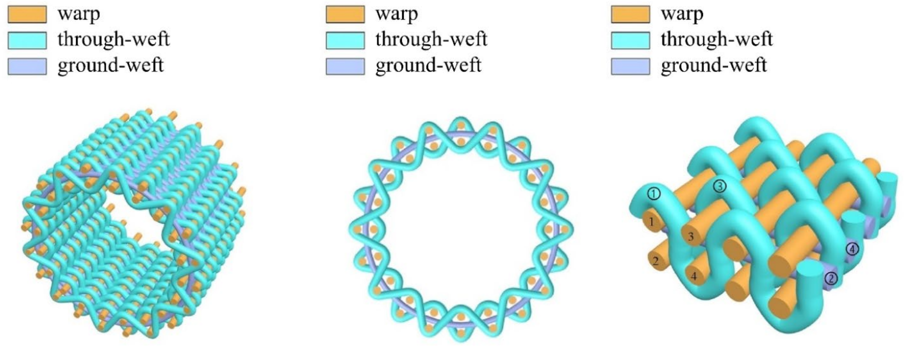
The principle of 3DTW construction

The ordinary tubular fabric is equivalent to a double-layer fabric with edge connections while with no connections in the middle part. When weaving with a double-layer structure, the principle of layered weaving is followed. The face weave could be formed by interweaving the warp and weft yarns on the face, while the warp and weft yarns on the back layer were interweaved to form back weave. When both the face and back weave are 3D fabrics with the same structure, this type fabric was called the 3DTW fabric. In other words, the 3DTW fabric is a tubular fabric with a 3D woven as the tube wall. In addition, the 3D woven fabric used for tube walls mainly includes orthogonal woven and angle-interlock woven.

3DTW fabric based on orthogonal woven as tube wall

According to the passage path through warp or weft yarn, 3D orthogonal tubular woven fabrics are divided into two common warp-through and weft-through types. Figure 3a shows the structure diagram of the weft-through orthogonal tubular woven fabric. Figure 3c is a schematic diagram of the structure of the tube wall, which is composed of two layers of orthogonal fabrics. It can be seen that 3D tubular woven fabric is constructed by three parts of yarns, and they are warp yarn, ground-weft yarn and through-weft yarn, respectively, which are represented by orange, purple and light blue. The warp yarns are evenly distributed in a circular direction, forming two layers of outer and inner layer. A layer of ground-weft yarn is located between two layers of warp yarn and perpendicular to the warp yarn, providing support for the structure. As shown in Fig. 3b, two through-weft yarns run through two warp layers and one ground-weft layer, and finally forming an overall tubular structure.

Figure 3c shows the schematic diagram of weft-through thickness orthogonal fabric. If it is used as face weave, the following rules can be obtained. Let R_{fj} and R_{fw} respectively represent the number of warp and weft yarns in the minimum repeating unit of the face weave. Let R_{bj} and R_{bw} respectively represent the number of warp and weft yarns in the minimum repeating unit of the back weave. Let R_{gj} and R_{gw} respectively represent the



(a) (b) (c)

Fig. 3 Schematic diagram of 3D tubular fabric based on weft-through thickness orthogonal weave from (**a**) perspective view, (**b**) cross-section view, and (**c**) tube wall number of warp and weft yarns in the minimum repeating unit of the tubular weave. Let the ratio between face warp yarn and back warp yarn is 1:1, the ratio between face weft yarn and back weft yarn is also 1:1. If the number of warp layers is N, then the number of ground-weft layers is N-1, and then $R_{fj}=2N$, $R_{fw}=2N$, $R_{bj}=2N$, $R_{bw}=2N$, $R_{gj}=4N$, $R_{gw}=4N$. For example, when $N=2$, $R_{fj}=4$, $R_{fw}=4$, $R_{bj}=4$, $R_{bw}=4$, $R_{gj}=8$, $R_{gw}=8$.

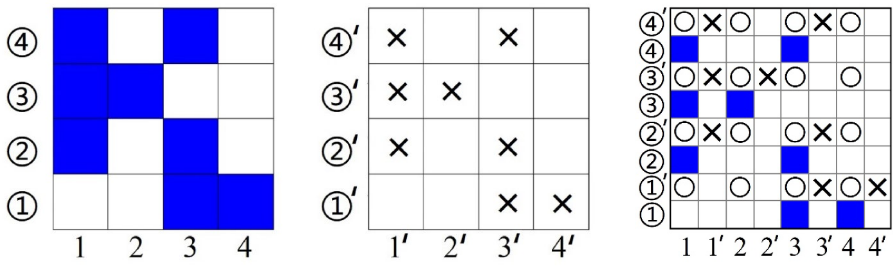
In order to obtain interweaving law in Fig. 3c, the warp yarns are numbered from top to bottom as following, warp yarns at top layer are of "1" and "3", warp yarn at bottom layer are of "2" and "4", respectively; Two through weft yarns are numbered "①" and "③" respectively; Two ground-weft yarns are also numbered by "②" and "④" respectively. The face weave diagram is given in Fig. 4a, where the serial number of warp yarn is expressed by "1" to "4", the serial number of weft yarn is expressed by "①" to "④", where "①" and "③" are through-weft yarns, "②" and "④" are ground-weft yarns. The face warp point was marked by "■", face weft point was marked with "□".

Figure 4b is the back weave diagram obtained by applying the "negative flip" method to Fig. 4a. The sequence number of warp yarn is represented by "1′" to "4′", and the sequence number of weft yarn is represented by "①′" to "④′". In order to distinguish different weave point, the back warp point was marked by " × ", while back weft point was also marked with "□".

Figure 4c shows the weave diagram of 3D tubular woven fabric. The weave diagram is designed by filling the face weave diagram (Fig. 4a) for the interaction points of odd columns and odd rows, and the back weave diagram(Fig. 4b) for the interaction points of even columns and even rows. At the same time, the interact point of all back weft yarn and face warp yarn needs to be lifted, that is, the position of the intersection between odd and even rows is indicated by "○".

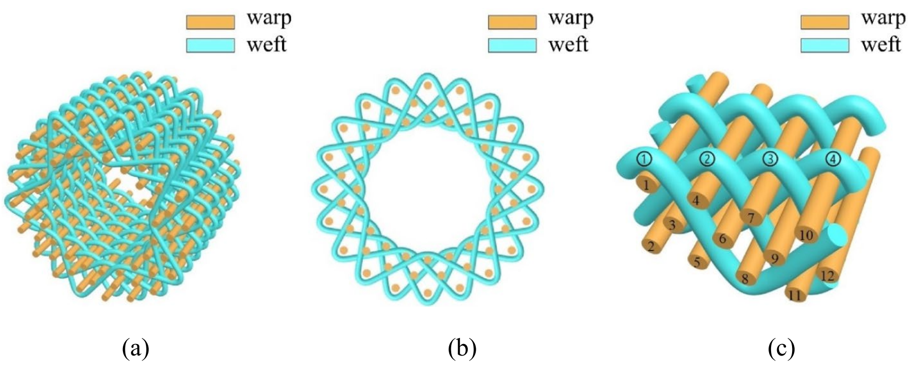
3DTW based on angle-interlock woven as tube wall

When 3D angle-interlock woven is selected as the tube wall, the weave diagram of the tube can be obtained by similar method. Figure 5 shows the schematic diagram of 3DTW based on weft through-thickness angle-interlock woven as the tube wall, where Fig. 5a is a perspective view, Fig. 5b is cross-section view and Fig. 5c is a schematic diagram of the tube wall, which is composed of three layers of warp yarns (marked by 1 to 12) fixed by four through-thickness weft yarns (mark by ① to ④) in a repeating unit.



(a) (b) (c)

Fig. 4 The weave diagram of 3DTW based on weft-through thickness orthogonal fabric. (**a**) face weave diagram; (**b**) back weave diagram; (**c**) tubular weave diagram



(a) (b) (c)

Fig. 5 Schematic diagram of 3DTW based on weft through-thickness angle-interlock woven from (**a**) perspective view, (**b**) cross-section view, and (**c**) tube wall

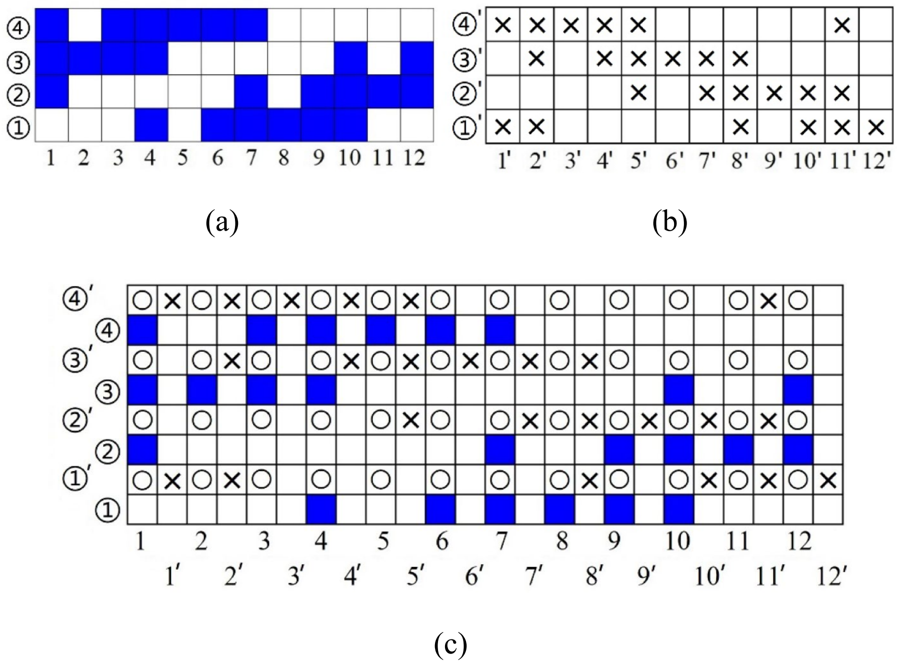


Fig. 6 Weave diagram of 3DTW based on weft through-thickness angle-interlock weave. **a** face weave diagram; **b** back weave diagram; **c** tubular weave diagram

Figure 6 shows weave diagram of 3DTW based on weft through-thickness angle-interlock fabric as the tube wall. According to the interweaving law, let the ratio between face warp yarn and back warp yarn is 1:1, the ratio between face weft yarn and back weft yarn is also 1:1, if the number of warp layers is N, then $R_{fw} = N + 1$, $R_{fj} = N \times (N+1)$, $R_{bw} = N + 1$, $R_{bj} = N \times (N+1)$, $R_{tw} = 2(N+1)$, $R_{tj} = 2(N \times (N+1))$. For example, when $N = 3$, $R_{fw} = 4$, $R_{fj} = 12$, $R_{bw} = 4$, $R_{bj} = 12$, $R_{tw} = 8$, $R_{fj} = 24$. Figure 6a shows the face weave diagram. Figure 6b shows the back weave diagram obtained by the “negative flip” method. Figure 6c shows the weave diagram of 3DTW. The meanings of each mark in Fig. 6 are the same as those in Fig. 4

Generation of 3DTW weave matrix

The references to construct 3DTW fabric model

Woven fabrics are formed by interweaving warp and weft yarns, which could be mapped into a two-dimensional matrix. When the warp is located above the weft, it is called a warp point and could be represented by element 1. When the weft yarn is located above the warp yarn, it is called a weft point and can be represented by element 0. Then, the 3DTW fabric could be woven according to the principle of layered weaving of tubular fabrics, with the tube wall being the 3D woven fabric. Similar to the above mapping method, a new mapping could also be established and a matrix model of 3DTW could be correspondingly constructed.

Matrix model of face weave and back weave of 3DTW

Weave matrix is not only a common model to reflect the interweaving law of warp and weft yarn, but also a basis for the computer to participate in fabric design and a means to improve design efficiency. The warp and weft yarns are equivalent to the columns and rows of the weave matrix respectively, and the lifting points of the warp and weft layers are represented by different element values. According to the construction principle of 3DTW, the matrix ***T*** can be obtained by embeding into each other according to the warp and weft yarn arrangement ratio in the face weave matrix ***F*** and the back weave matrix ***B***, where the layer lifting point element was set, that is, the face warp yarn must be lifted at the intersection of the back weft yarn and the face warp yarn, as a result achieving the face-back layered weaving.

Figure 7 shows the matrix model corresponding to face weave (Fig. 7a) and back weave (Fig. 7b) with two layers of weft through-thickness orthogonal woven as the tube wall. The face weave matrix ***F*** and the back weave matrix ***B*** are the same dimensional matrices with the same number of rows and columns. For the sake of distinction, the face weave matrix ***F*** uses elements "1" and "0" to represent the warp and weft points, respectively. While, the back weave matrix ***B*** uses elements "3" and "0" to represent the warp and weft points, respectively.

Matrix model of 3DTW

When the ratio of face and back warp yarn, and face and back weft yarn is 1:1, the number of rows and columns of matrix ***T*** is two times that of matrix ***F*** or ***B***. The matrix ***T*** can be established based on three steps. In step (1), the face weave matrix ***F*** is established according to the interweaving law of the tube wall; In step (2), according to the "negative flip" method, the back weave matrix ***B*** can be obtained by element replacement and adjustment of the column order in turn of the matrix ***F***; In step (3), the embedding

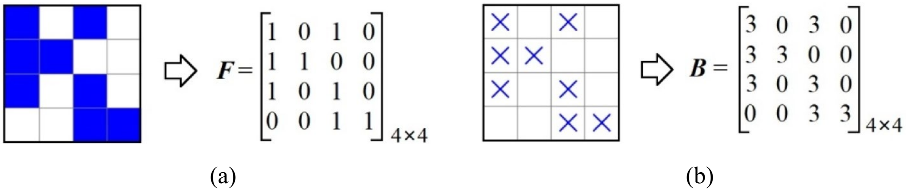


Fig. 7 Weave matrix model of face weave and back weave (**a**) face weave and (**b**) back weave

$$\boldsymbol{K}_1 = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \qquad \boldsymbol{K}_2 = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \qquad \boldsymbol{K}_3 = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \qquad \boldsymbol{C} = \begin{bmatrix} 5 & 5 & 5 & 5 \\ 5 & 5 & 5 & 5 \\ 5 & 5 & 5 & 5 \\ 5 & 5 & 5 & 5 \end{bmatrix}$$

Fig. 8 Matrix model of $\boldsymbol{K}_1$, $\boldsymbol{K}_2$, $\boldsymbol{K}_3$ and $\boldsymbol{C}$

of matrix $\boldsymbol{F}$ and matrix $\boldsymbol{B}$ can be realized through matrix Kronecker product operation based on the arrange ratio of warp and weft yarn; Finally, the matrix $\boldsymbol{T}$ is get by assigning the lifting point at the interleaving of back weft and face warp yarn.

The matrix model construction methods of 3DTW in step (1) have been discussed in (X. Wang et al., 2020; X. Wang et al., 2019). In step (2), the "negative flip" of matrix $\boldsymbol{F}$ can be broken down into two steps of "negative" and "flip", the former can convert the element "0" in matrix $\boldsymbol{F}$ to "3", and then convert "1" to "0" while the latter can order the column vectors of matrix $\boldsymbol{F}$. In MATLAB software, "negative" and "flip" can be finished by the "Find" and "Fliplr" functions, respectively. In step (3), The Kronecker product processing process of face and back weave matrix can be realized by formula (1) (X. Wang et al., 2015).

$$T = F \otimes K_1 + B \oplus K_1 + C \otimes K_3 \tag{1}$$

where $\otimes$ represents Kronecker product operation; Matrix $\boldsymbol{F}$, $\boldsymbol{B}$ and $\boldsymbol{T}$ represent face weave matrix, back weave matrix and 3D tubular weave matrix, respectively. Matrix $\boldsymbol{C}$ and matrix $\boldsymbol{F}$ or $\boldsymbol{B}$ have the same dimension, and their elements are "5". The function of Kronecker product for matrix $\boldsymbol{F}$, $\boldsymbol{B}$ with matrix $\boldsymbol{K}_1$ and $\boldsymbol{K}_2$ is to complete the process of embedding the face warp and back warp in 1:1, face weft and back weft in 1:1, while the function of Kronecker product for matrix $\boldsymbol{C}$ and matrix $\boldsymbol{K}_3$ is to complete the process of lifting the face warp yarn when weaving back weft. Here $\boldsymbol{K}_1$, $\boldsymbol{K}_2$, $\boldsymbol{K}_3$, and $\boldsymbol{C}$ are shown in Fig. 8. The above process can be completed by Kron function of MATLAB.

Through the above analysis, the generation of matrix $\boldsymbol{T}$ can be divided into three steps. Firstly, the elements of face weave matrix $\boldsymbol{F}$ are assigned to the positions of odd columns and odd rows in $\boldsymbol{T}$ in turn, which is completed by $\boldsymbol{F} \otimes \boldsymbol{K}_1$; Secondly, the elements of the back weave matrix $\boldsymbol{B}$ are successively assigned to the positions of even columns and even rows in $\boldsymbol{T}$, which is completed by $\boldsymbol{B} \otimes \boldsymbol{K_2}$; Thirdly, the position where the odd and even rows intersect in the matrix $\boldsymbol{T}$ is assigned the element "5", and the process is completed by $\boldsymbol{C} \otimes \boldsymbol{K_3}$.

An example of the establishment of 3DTW

When two-layer weft through-thickness orthogonal in Fig. 3c is selected as tubular wall, the establishment process of 3DTW matrix $\boldsymbol{T}$ is shown in Fig. 9. The number of warp yarn and the number of weft yarn in repeat unit of face weave $\boldsymbol{R_{fj}}=4$, $\boldsymbol{R_{bw}}=4$ respectively. That is, the face weave matrix $\boldsymbol{F}$ is with 4 rows and 4 columns, and the element "0" is replaced by "3" through the find function in the MATLAB program, and then the element "1" is replaced by "0" to complete the "negative" effect. Fliplr function is used to achieve the "flip" process, and then back weave matrix $\boldsymbol{B}$ with 4 rows and 4 columns is obtained. Let the arrangement ratio between the warp yarns in the face weave and back weave is 1:1, and arrangement ratio between weft yarns in the face weave and back weave is also 1:1, then the matrix $\boldsymbol{K_1}$, $\boldsymbol{K_2}$, $\boldsymbol{K_3}$ and $\boldsymbol{C}$ are set as shown in Fig. 8. Finally, according to formula (1), through matrix Kronecker product operation, the matrix $\boldsymbol{T}$ of 3DTW can be obtained. By writing the MATLAB program, the matrix $\boldsymbol{T}$ can be automatically calculated based on formula (1).

In addition, the plot function provided by the MATLAB program can realize the drawing of the weave diagram. The process is using a loop to judge different elements of the matrix one by one, and then draw corresponding symbols. For example, the matrix elements "1", "3", "5" and "0" correspond to the symbols of "■", "×", "◯" and "□", respectively.

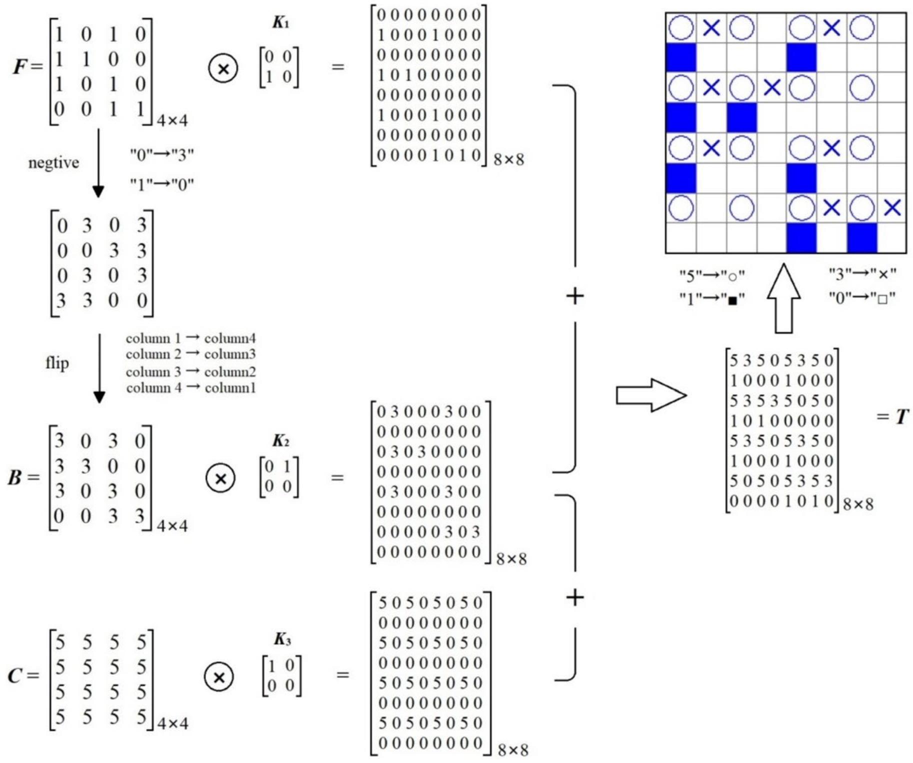
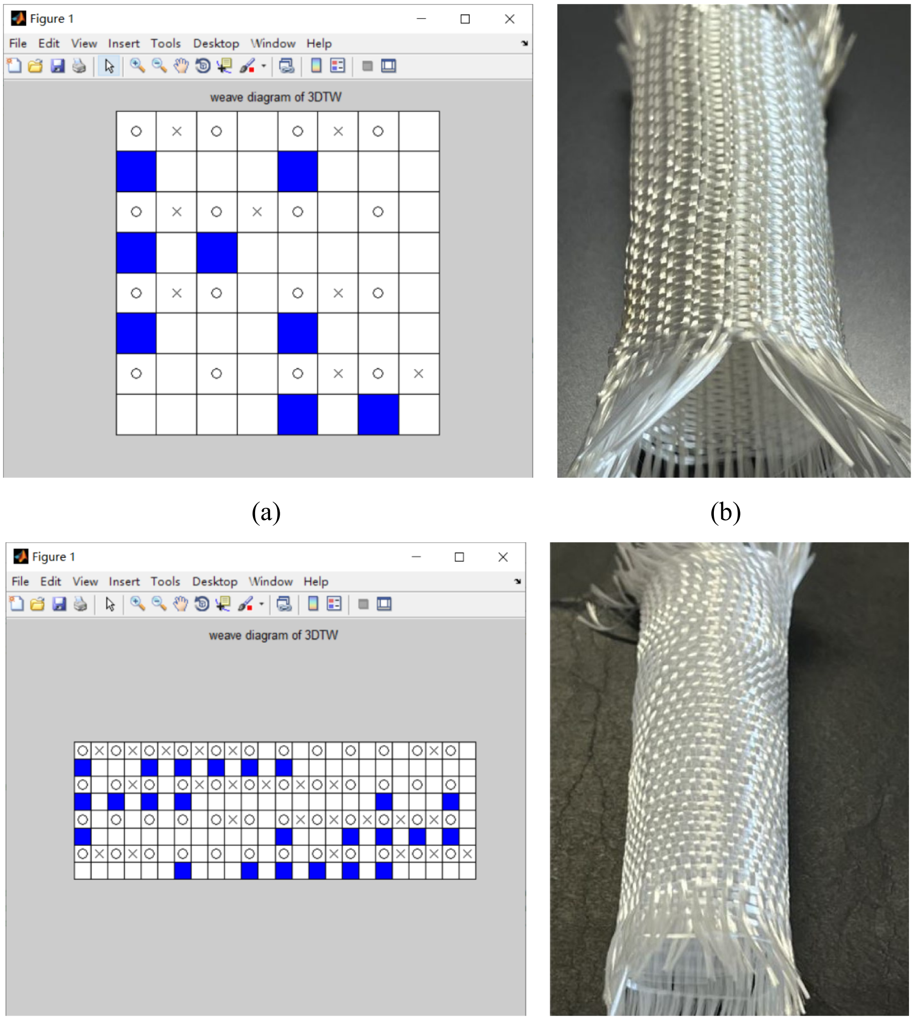


Fig. 9 The establishment process of weave matrix $\boldsymbol{T}$ of 3DTW

The above example indicates that the proposed matrix model construction method can realize the rapid generation of matrix model of 3DTW with different weave as tubular wall, and can also optimize the design of this kind of fabric.

The validation of hypothesis

To verify the feasibility of the proposed method, the related samples were weaved experimentally using SGA598 loom (Jiangsu Tongyuan Company, China). Figure 10 gives weave diagrams and the specific weaved preforms based on the above proposed method. In Fig. 10a, the 3DTW diagram of two-layer weft-through thickness orthogonal fabric is provided, and Fig. 10b presents the related woven samples according to the Fig. 10a, which verify the feasibility of our proposed method. Correspondingly, Fig. 10c gives a weave diagram of 3DTW of three-layer weft-through thickness angle-interlock fabric,



weave diagram of 3DTW

○	×	○		○	×	○	
■				■			
○	×	○	×	○		○	
■		■					
○	×	○		○	×	○	
■				■			
○		○		○	×	○	×
				■		■	

(a) (b)

weave diagram of 3DTW

○	×	○	×	○	×	○	×	○	×	○		○		○		○		○		○	×	○	
■				■		■		■		■		■											
○		○	×	○		○	×	○	×	○	×	○	×	○	×	○		○		○		○	
■		■		■		■												■				■	
○		○		○		○		○	×	○		○	×	○	×	○	×	○	×	○	×	○	
■												■				■		■		■		■	
○	×	○	×	○		○		○		○		○		○	×	○		○	×	○	×	○	×
						■				■		■		■		■		■					

(c) (d)

Fig. 10 The weave diagrams of 3DTW and their weaved samples. (**a**) 3DTW diagram of two-layer weft-through thickness orthogonal fabric and (**b**) related weaved sample; (**c**) 3DTW diagram of three-layer weft-through thickness angle-interlock fabric and (**d**) corresponding weaved sample and Fig. 10d is a sample woven according to the Fig. 10c, which simultaneously verify the practicability of the proposed method.

Therefore, the above two cases demonstrated that the proposed method could automatically generate a matrix of the 3DTW and draw the weave diagram based on the read face weave matrix. The weaved samples could verify the feasibility and practicability of the weaved diagrams and the proposed method in the paper.

Conclusions

In this paper, a design method of 3DTW based on normal loom is presented. 3D fabric is selected as the tube wall (face weave), then the back weave can be obtained according to the "negative flip" method, and the 3DTW structure is constructed according to the principle of layering weaving. The construction method of matrix model of 3DTW is provided. Different matrix elements are used to represent warp and weft points in the face weave and the back weave, and the face warp lift point during the weaving of the back weft. The generation matrix model of 3DTW is achieved by using the MATLAB function, which include element replacement, matrix reordering to achieve "negative flip", matrix Kronecker product operation, and automatic drawing of weave diagram. By analyzing the structure of 3DTW, the automatic generation method for the weave matrix of 3DTW structure possesses good reference value to improve the design efficiency of this type of reinforcement structures.

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Author contributions
XW conceived the original idea of this study and participated in design and coordination as well as manuscript drafting. SL and DX were responsible for the implementation of the project.

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Availability of data and materials
The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

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The authors declare that they have no competing interests.

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