Computation & theory

Process design of variable fiber content in layers of needle-punched preforms

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ABSTRACT

The needle-punched composite preforms have great potential to be used in the components with aerospace industry. The variable fiber content in layers of needle-punched preforms can affect the structure and properties of the formed composites, where the fiber content distributions can be designed in the needle-punched direction by the needle punching process and compaction process. A needle-punched fiber analysis method is established to determine the fiber content introduced in the thickness direction during the needle punching process. An artificial neural network (ANN) is constructed between the remaining fiber content in layers and needle punching process parameters. Based on the ANN, the needle punching process is designed in order to satisfy the specified requirements of fiber content distributed in the needle-punched preform. The maximum error between the designed fiber content and the target value is 1.18%. An improved compaction theoretical model is also applied to obtain the variation of fiber content in layers. The fiber content can be accurately obtained by controlling the pressure of needle plate and the pressure can also be set to satisfy the thickness requirements of needle-punched preforms. The compaction theoretical model is further validated by compressive experiment of the needle-punched preforms. The relative error between experimental value and theoretical value is 3.49%. This work can effectively guide the design of variable fiber content in layers of needle-punched preform.

Introduction

The design and production of carbon fiber preform has an important effect on the structure and properties of composite materials. For example, the improvement in the preform molding process could make the material more lightweight [1], the properties of composite materials could be greatly improved by additive manufacturing technology to produce carbon fiber preforms [2] and the microstructure and compressive plasticity of composites could be significantly improved by adjusting the pressure infiltration parameters of the preforms [3]. The carbon fiber needle-punched preforms can be used as the reinforced skeleton of the needled composites, which have been widely used in solid rocket engine throat lining, nozzle expansion segment, aircraft brake disk and other components [4–6]. The mechanical and thermal properties of the needled composite materials will be further improved by improving the forming process of the needle-punched preforms [7, 8]. In addition, the design of needle-punched preforms is strong due to flexible needle punching process, where the gradient distributions of fiber content in the needle-punched direction as the variable density needle-punched preforms can be obtained easily. The variable density needle-punched preforms can greatly improve the properties of the needled composites as functionally graded materials, which can enhance and expand the application of the needled composites. Thus, it is essential to develop the needle punching process and compaction process design method of the variable density needle-punched preforms.

The fiber contents in different layers of the needled preforms are greatly depended on the number of needle-punched fiber. Considerable attentions are paid upon the effect of needle punching process on the fiber content qualitatively [9, 10, 13]. Liu [9] found the short fibers in the fiber net were mainly carried to thickness direction by needle hooks. Liu [10] analyzed the influence of different needling processes on fiber content in thickness direction. Besides, the needle type and needle abrasion properties also can influence the fiber content transferred in the thickness direction [11, 12]. Xie [13] used the virtual fibers establishing a nonwoven geometric model and simulated the needle punching process by finite element method. However, the numerical method is inefficient and time-consuming to qualitatively calculate the needle-punched fiber content. Thus, it is necessary to establish the relationship between needling process and the needle-punched fiber content using a theoretical analysis method.

In order to improve the calculate efficiency, some surrogate models, such as artificial neural networks (ANNs), have been widely used in designing material parameters. The ANN has been successfully applied in the material design field, such as designing glass fiber-reinforced polymer bar structure [14], improving temperature uniformity in polymer composites microwave curing process [15], and optimizing parameters for enhanced xylitol production [16]. Thus, it is an effective way to establish appropriate needle punching process design model based on an ANN. The design of needle punching process is searched quickly according to the needle-punched fiber content.

The compaction process is key factor affecting the final fiber content in different layers. Many scholars have studied the change of fabric thickness in the process of compaction. For example, a theoretical model [17] or an experiment [18] to study the relationship between fabric thickness and compressive load. In addition, Chen [19] and Hu [20] developed a nonlinear compaction model to calculate the fiber content. Some scholars also studied the change of fiber bundle cross section during compaction [21–23]. However, the current studies have focused on fabrics containing only in-layer fibers. Due to the existence of needle-punched fibers, it is necessary to revise the existing compaction model to study the compaction law of needle-punched preforms and realize the design of compaction process.

In the present study, the geometric model of net fibers and needle hooks are established to simulate the process of grasping fibers. The needle-punched fiber content is calculated by statistical results. Thus, a theoretical analysis method about needle-punched fiber content of different needle punching process is proposed. Based on studying the fiber content in the needle punching process, an artificial neural network is established to design the needle punching process to meet the requirements of fiber content in layers. The relationship between the needling processes and the fiber content in layers is established by this method which improves the design efficiency and saves the design time. In addition, an improved compaction model is established to calculate the

relationship of compaction rate and fabric pressure changing with the thickness of the needle-punched preforms. This compaction model can be used to control suitable fabric pressure to design the thickness of layers in preforms. The fiber content in layers will change with the change of layer thickness. Lastly, a compressive experiment of the needle-punched preforms is carried out to select empirical coefficient and further validate our model. This model considers the effect of needle-punched fibers on the compaction process. This study can provide a theoretical basis for the design of variable density needle-punched preforms.

Design of needle punching process parameters

Needle-punched fiber content analysis model

The carbon fiber cloth/net needle-punched preforms can be prepared by using the needle punching process. The needle-punched process of the preforms is shown in Fig. 1a.

The short fiber net and long fiber cloth are alternately laminated. A layer of fiber net and a layer of long fiber cloth are defined as a unit layer. The needles on the needle plate with the reciprocating movement are punched upon the laminates to introduce the fiber into the thickness direction (z-direction). Thus, the needle-punched preforms with interlayer connection structure can be obtained [24].

The needle punching process can be adjusted by some parameters, such as needling depth and needling number, needle arrangements and the stepped

Figure 1 Needle punching process and needle plate, **a** Needle punching process of the preforms **b** Four-row needle plate.
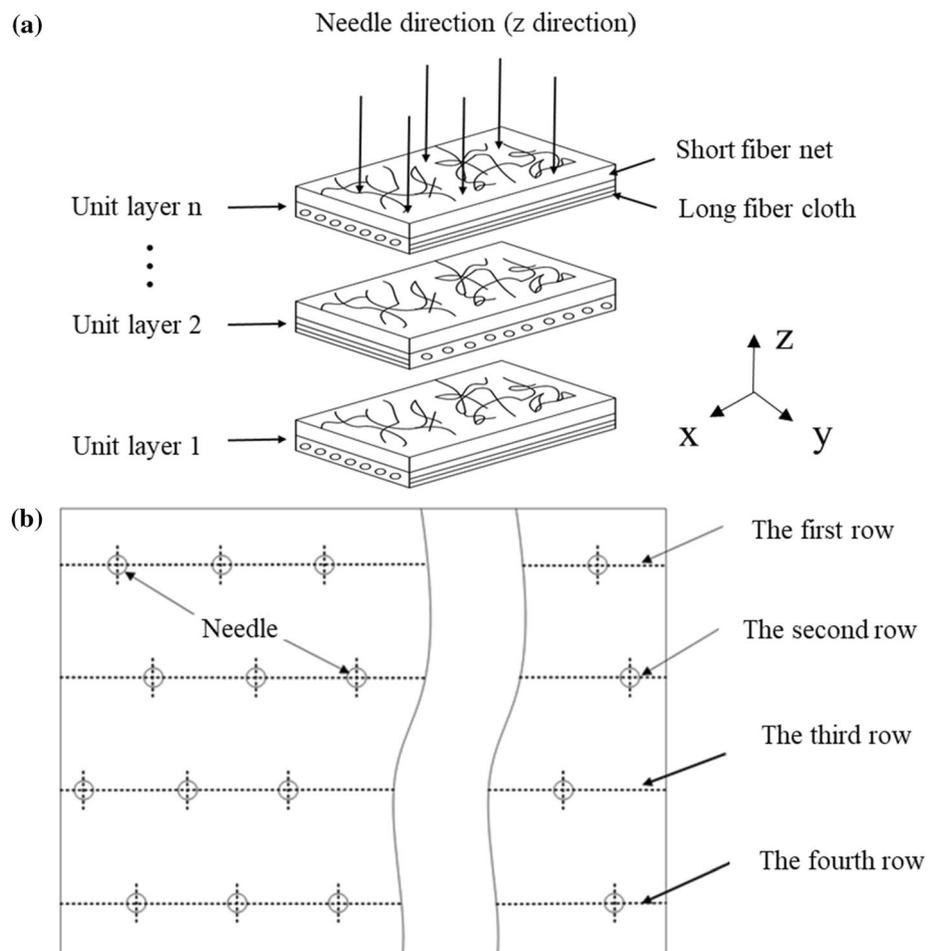
size. These parameters can greatly affect the fiber content distribution of the needle-punched preforms. In the present study, the parallelogram and four-row needle arrangements are adopted as shown in Fig. 1b. The number of needles on the needle plate can determine the number of needle regions [25]. The range of needle punching process used in this paper is shown in Table 1.

The short-cut fiber net is the main source of *z*-direction fiber in the needle-punched preforms. The in-plane fibers can be introduced into *z*-direction by the needle punching. The needle grasping fiber process is sketched as shown in Fig. 2a. A virtual fiber model is used to analyze the volume of *z*-direction fiber. A short-cut fiber net with certain fiber content is generated firstly. The fibers are viewed as straight segments in the generated fiber net. The needle code selected is 15 × 18 × 36 C333, and the needle hook shape can be considered a trigonal prism. The triangle height of working part is 0.58 mm [26]. In the

actual production process, when the needle is punched into the short-cut fiber net, the needle will bring a certain number of short-cut fibers into the *z*-direction. Therefore, a trigonal prism of the same size as the working part is generated at a random position of the generated fiber net. When the straight segment intersects the trigonal prism, this fiber is thought to be grasped by the needle. The whole fiber grasping process is completed on the MATLAB 2014 platform. The short-cut fibers grasped by the trigonal prism needle can be recorded in each needle-punching as shown in Fig. 2b.

In this process of grasping, the fiber length range in the short-cut fiber net is between 40 and 80 mm, the fiber type is T700 and the diameter of fiber is 7 μm [27]. The initial size of short-cut fiber net is 80 mm × 80 mm × 0.8 mm, and the surface density of short-cut fiber net is 140 g/m^2. Thus, the fiber mass contained in short-cut fiber net is 0.896 g, where the density of fiber is 1.78 g/cm^3, the volume of fiber is 503.4 mm^3, and the initial fiber volume content is 9.83%.

The needle grasping fiber results are statistically analyzed by 500 virtual needle grasping fiber simulations. The probability distribution of the percentage of grasping fiber (the ratio of the number of grasping fibers to the number of whole net fibers) is shown in Fig. 3.

Table 1 Range of needling process parameters

Needling process parameters	Lower limit	Upper limit
Needling depth (mm)	10.0	20.0
Needle arrangement (rows)	4	9
Step size (mm)	6.0	12.0
Needling number (time)	1.0	4.0

Figure 2 Needle grabbing fiber simulation **a** Needle grabbing fiber process, **b** Virtual fiber model for simulating the needle grasping fiber process.
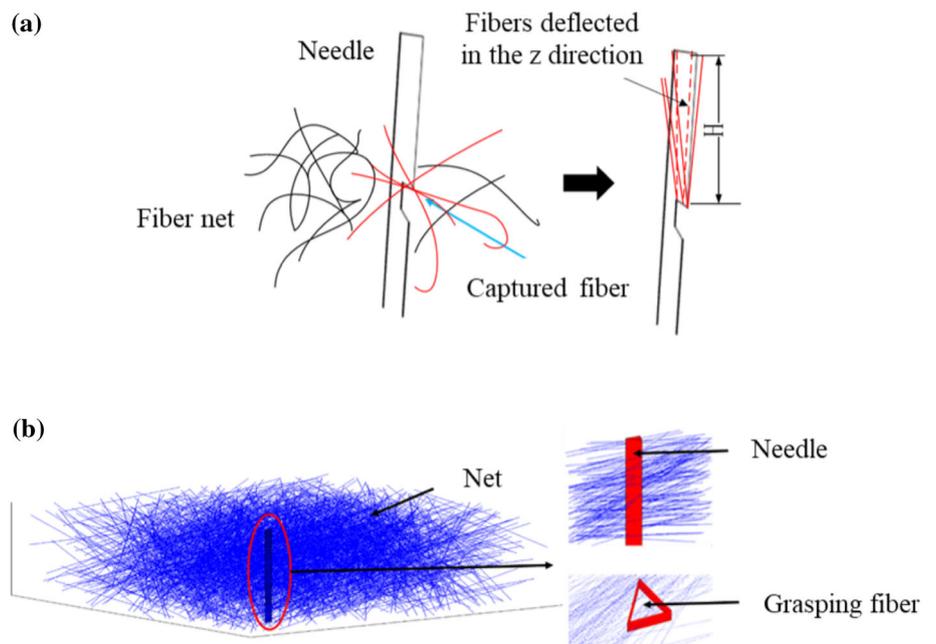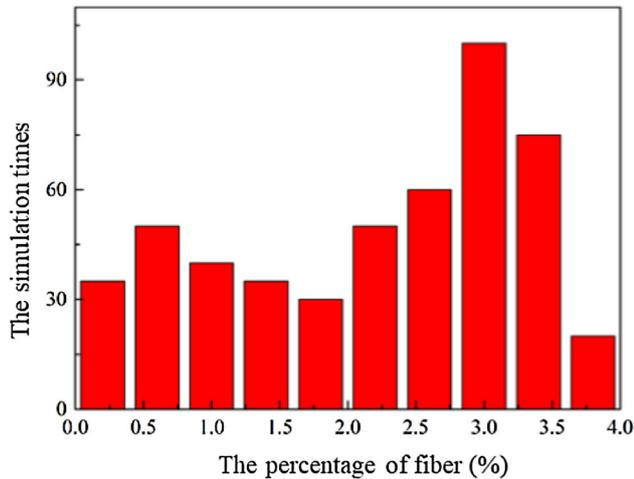
Figure 3 Probability distribution of the percentage of needle grasping fiber.

Because the fiber is distributed randomly, the needle gasping fiber number exhibits random characteristic. This means that the number of fibers that the needle grabs is different each time. The fiber density generated is different in different areas of the fiber net, the fiber density in the center is much higher than that in the edge area of the fiber net, and the position of the needle entering the fiber net is also different. Thus, the closer the needle position is to the center of the fiber net, the more fiber content the needle grabs.

It was found in reference [28] that the number of fibers transferred to z-direction was the largest in the surface layer, while the needle carries much less fiber from other layers than from the surface. In the present study, it is assumed that the number of fibers introduced into the z-direction all come from the surface layer.

The total fiber volumes introduced into z-direction of the needles during one needle punching can be expressed as

$$V_z = \sum_{j=1}^{M} \sum_{i=1}^{N} v_{zij} \tag{1}$$

where N is the number of short-cut fiber net punched by needles, M is the number of needles punching the short-cut fiber net, and v_{zij} is the fiber volume in the current layer carried by a needle, which can be expressed as

$$v_{zij} = \pi r^2 \cdot n_r \cdot L_f \tag{2}$$

where n_r is the number of fibers grasped by a needle, L_f is the fiber length introduced into the z-direction, and r is the radius of the fiber. In addition, the parameters N, M, L_f can be obtained statistically from the needle-punched preform model with specific needle punching process, and the model can be described in detail in our previous work [25, 29]. Based on the above analysis, the fiber contents in the z-direction and the remaining in the net of the needle-punched preforms can be calculated for the specific needle punching process.

Needle punching process design based on ANN

Using the needle-punched fiber content analysis model, the relationship of needle-punched fiber content and needle punching process parameters can be obtained. But the fiber is captured using the model each time, the time consumed is approximately 310 s. Thus, the model is not convenient to use if the large number of layers need to be designed. To design the variable fiber content needled preforms quickly, an ANN is used to establish a one-to-one correspondence between the needle punching process parameters and the remaining fiber content in layers after needle punching. The data set used in the ANN is calculated by the fiber content analysis method in "Needle-punched fiber content analysis model" section. The set fiber content as the target value is transferred to the network model. The needle punching process can be obtained to satisfy the target value. The overall calculation process is shown in Fig. 4.

The 1000 sets of data are generated by using the needle-punched fiber content analysis method for ANN to learn the relationship between needle punching process and fiber content. The proportion of training data, validation data and test data are 0.7, 0.15 and 0.15, respectively. The mean square error (MSE) function as the loss function of the ANN is used to evaluate the ANN performance as shown in Eq. (3). The change of loss function with the number of iterations is shown in Fig. 5, whose maximum relative error is shown in Table 2.

$$MSE = \frac{1}{n} \sum_{i=1}^{n} (y_n - \widehat{y})^2 \tag{3}$$

Figure 4 Needle punching process parameter design process.
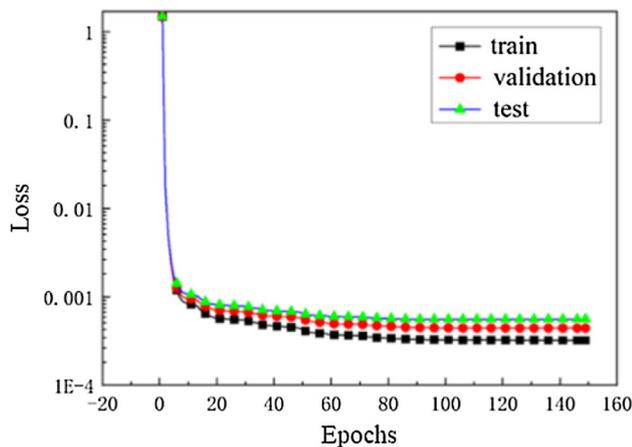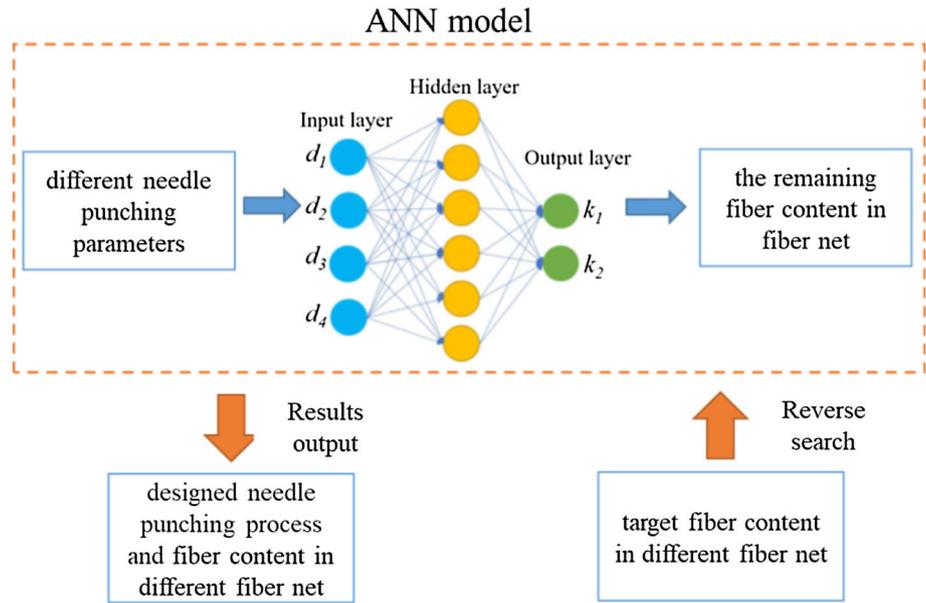
Figure 5 The change of loss function during ANN calculation.

Table 2 Relative errors of ANN for different data sets

Data set	Training data	Validation data	Test data
Relative error	6.43%	6.78%	6.93%

where n is the number of data, y_n is the prediction value of ANN, and $\widehat{y}$ is the real value.

It can be seen from Fig. 5 that when the ANN runs to about 150 steps, the loss function does not continue to decrease and become convergence. At this point, the maximum relative errors between the network output values and the real values of the three data sets are all below 7%. Thus, the constructed ANN has good performance.

In the present study, an optimal design of the needle-punched preforms with five layers is carried out. When designing the needling process, it is assumed that the thickness of each layer is not changed and the effect of compaction process on variation rule of fiber content in the preform is not considered. The corresponding needle punching process is designed to make the remaining fiber content in short-cut fiber net layers show gradient change. The fiber content becomes 95%, 90%, 85%, 80% and 75% of the original, respectively. The density of the fiber net also changed with the change of fiber content. The remaining fiber content and the density of each layer is shown in Table 4.

The needle punching process is designed based on the ANN is shown in Table 3. The fiber content obtained by the ANN is shown in Table 4. It can be seen from Table 4 that the fiber content of layer obtained by needle punching process optimized by ANN is basically consistent with the target value, whose maximum error is 1.18%. And the standard errors between design values and target values of the fiber content and the net density are 0.043 and 0.00123. Thus, the established ANN model can design the needle punching process parameters by setting target fiber content without compaction. And the optimal remaining fiber content also can be obtained with specific needling process. It takes less than 1 min to design the needle-punched processes by

Table 3 Designed needle punching process parameters

Net number	Needling number (time)	Needle arrangements (rows)	Needling depth (mm)	Stepped size (mm)
1	1	9	14	12
2	2	8	13	10
3	3	5	16	10
4	3	7	18	12
5	4	6	15	8

Table 4 Remaining fiber content and the density of fiber net in the needle-punched preform

Net number	Fiber content target value (%)	Fiber content design value (%)	Net density target value (g/cm^3)	Net density design value (g/cm^3)
1	9.34	9.23	0.167	0.164
2	8.85	8.92	0.158	0.159
3	8.36	8.44	0.149	0.150
4	7.86	7.89	0.140	0.140
5	7.37	7.37	0.131	0.131

using the ANN model, which greatly reduces the design time and improves the design efficiency compared with other methods.

Design of compaction process parameters

Compaction model of the needle-punched preforms

In order to make the preform structure close, the preform will be compacted in the production. The compaction process is usually used after the needling process. During the compaction process, the thickness of the needle-punched preforms decreases, and the fiber volume content will increase. So, the compaction process determines the final in-plane fiber content of the preform. The carbon fiber cloth in the needle-punched preforms exhibits the neat and compact state, which is difficult to be compressed. Thus, the volume of the needle-punched preforms is mainly attributed to the short-cut fiber net compaction process. When the fabric is subjected to the pressure, the curve of the fabric thickness with pressure can be divided into three stages: initial linear stage, nonlinear stage and final linear stage [18]. It is assumed that the total volume of fibers does not change during compaction. The relationship between compaction rate of the fabrics and thickness can be written as [18]:

$$C_b(T) = \frac{1 - (s_0 T_0/T)}{1 - s_0} \left(\frac{1 - T_f/T}{1 - T_f/T_0} \right)^k C_{b0}$$
$$+ \left[2 - \frac{s_0 T_0}{T} - \left(1 - \frac{s_0 T_0}{T} \right) \left(\frac{1 - T_f/T}{1 - T_f/T_0} \right)^k \right] C_s$$

(4)

The relation between the pressure and the fiber volume content can be expressed as:

$$P = \frac{1}{C_b(s)} \left(1 - \frac{s_0}{s} \right)$$

(5)

where C_b is the compaction rate of the fabrics, s is the fiber volume content during compaction, s_0 is the initial fiber volume content, C_{b0} is the initial compaction rate of the fabrics, C_s is the fiber compaction rate, k is the empirical coefficient, T is the thickness of the fabrics during compaction and T_f is the final thickness of the fabrics.

The fiber compaction rate C_s can be calculated as:

$$C_s = 1/K_s$$

(6)

where K_s is the fiber bulk modulus. The initial compaction rate C_{b0} can be calculated as:

$$C_{b0} = -\frac{1}{T_0} \frac{\Delta T}{\Delta P} = -\frac{1}{T_0} \frac{dT}{dP}\bigg|_{p \to 0}$$

(7)

where T_0 and $\left.\frac{\mathrm{d}T}{\mathrm{d}P}\right|_{p \to 0}$ can be measured experimentally. The empirical index k can also be determined by experimental data fitting.

Similarly, the needle-punched preforms also have three similar stages in the compaction process. Owing to the needle-punched fibers, the final fiber volume in the short-cut fiber net is not equal to the initial fiber volume. The variation of fiber content in the short-cut fiber net can be expressed as

$$sV \approx s_0 V_0 - V_z \tag{8}$$

$$sT \approx s_0 T_0 - V_z/S_a \tag{9}$$

where V_z is the volume of needle-punched fiber, S_a is the upper surface area of the short-cut fiber net.

Using Eq. (4), Eq. (8) and Eq. (9), the relationship between compaction rate of the needle-punched preforms and thickness can be modified as

$$C_b(T) = \frac{1 - (s_0 T_0/T - V_z/(S_a T))}{1 - s_0} \left(\frac{1 - T_f/T}{1 - s_0 T_f/(s_0 T_0 - V_z/S_a)} \right)^k C_{b0}$$
$$+ \left[2 - \left(\frac{s_0 T_0}{T} - \frac{V_z}{S_a T} \right) - \left(1 - \frac{s_0 T_0}{T} + \frac{V_z}{S_a T} \right) \left(\frac{1 - T_f/T}{1 - s_0 T_f/(s_0 T_0 - V_z/S_a)} \right)^k \right] C_s \tag{10}$$

The relationship between the pressure and the fiber volume content can be expressed as

$$P = \frac{1}{C_b(s)} \left(1 - \left(\frac{s_0}{s} - \frac{V_z}{S_a T_0 s} \right) \right) \tag{11}$$

Thus, the z-direction fiber volume can be obtained from the needle-punched fiber content analysis model in "Needle-punched fiber content analysis model" section. And other parameters can be obtained by experiment. According to the above analysis, combined with the needle-punched fiber content analysis theoretical model, the final compaction process parameters can be determined.

Study of fiber content during compaction

This section studies the change of fiber content in different layers with different fabric pressure. The final in-plane fiber content of the fiber net with the specific pressure are calculated. According to the theoretical compaction model, the change rule of compaction rate with short-cut fiber net thickness can be obtained by Eq. (10) as shown in Fig. 6. The pressure of the needle-punched preforms can be calculated by Eq. (11). The curve of pressure and the short-cut fiber net thickness is provided in Fig. 7. In

this study, the needling process of each short-cut fiber net layers uses the values in Table 3.

The initial compaction rate C_{b0} is calculated by compression experiment of needle-punched preform that is introduced in "Selection of empirical coefficient" section. The fiber bulk modulus can be calculated by the formula (12):

$$K_s = \frac{E_s}{3(1 - 2v)} \tag{12}$$

where E_s and v are transverse modulus and Poisson ratio of T700 carbon fiber, and the value of them are 18.22 GPa and 0.27 [27]. The other parameters in "Needle-punched fiber content analysis model" section for the theoretical calculation are adopt. The calculations are shown in Table 5.

It can be found in Fig. 6 that all curves for different empirical coefficients have the similar tendency. The layer thickness increases gradually with the increase of the compaction rate. Due to the difference of fiber content introduced into the z-direction, the closer surface layer is, the more the compaction rate increases. In addition, with the increase of the empirical coefficient, the compaction rate will increase under the same thickness. It can be seen from Fig. 7 that the curve of thickness variation with pressure can be divided into three stages: linear segment, nonlinear segment and linear segment, which has the same trend as the curve of two-dimensional fabric compaction [19, 20]. As the pressure of the needle plate increases, the thickness of the needle-punched preforms decreases, and the pressure on each layer is different.

When the fabric pressure of each fiber net layer is 1 MPa, the thickness and the in-plane fiber content after compaction are shown in Table 6. As can be seen, there are differences in the change of fiber net thickness and the fiber content with different empirical coefficients. When $k = 2$, the fiber net thickness after compaction is the smallest, which leads to the largest increase of fiber content. The fiber content of fiber net becomes 1.81 times of the original. Compared with the fiber content in Table 4, the fiber content of the first fiber net is 1.93 times as much as the fiber net only after needle punching. When $k = 3$ or $k = 4$, the thickness of the compacted fiber net is greater than the fiber net when $k = 2$, and the increase of fiber content in the fiber net is smaller. Thus, by controlling the pressure of the needle plate, the thickness of each layer in the needle-punched
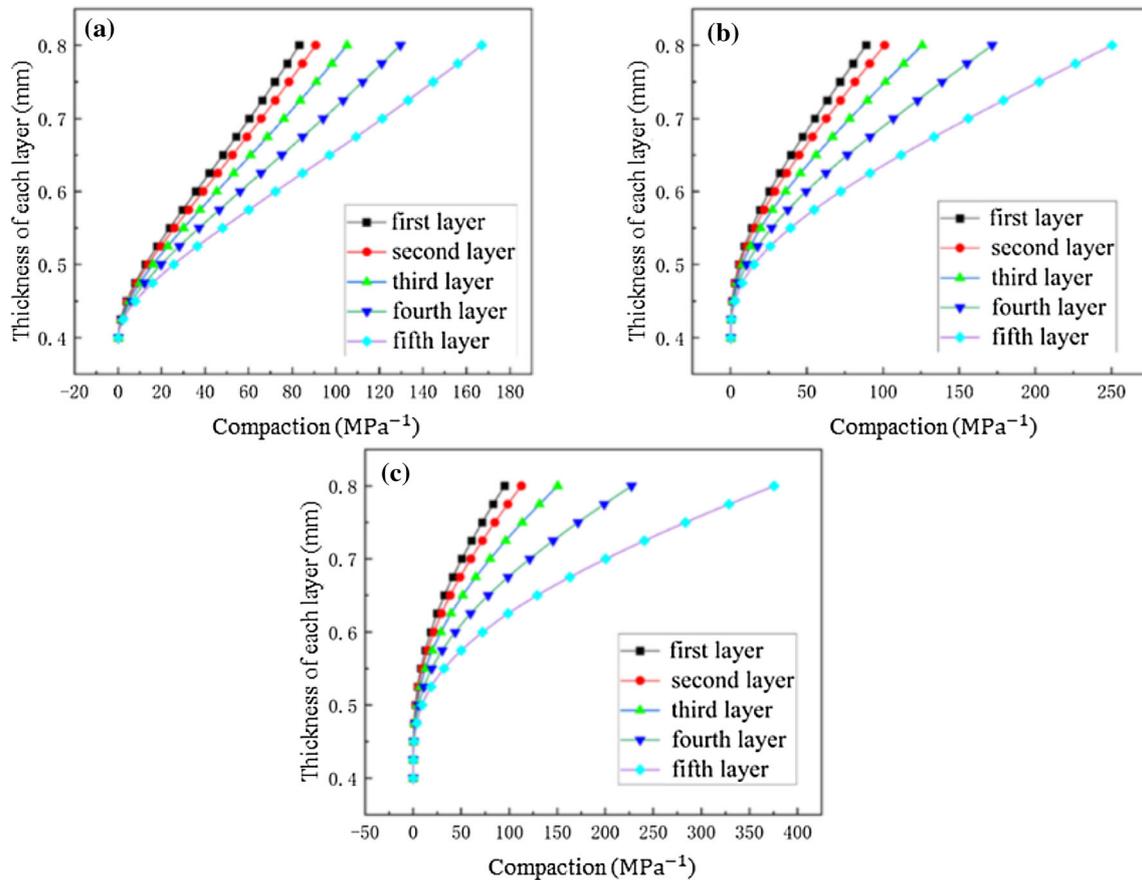
Figure 6 Compaction rate of different empirical coefficients changing with thickness, **a** Empirical coefficient $k = 2$, **b** Empirical coefficient $k = 3$, **c** Empirical coefficient $k = 4$.

preform and the final in-plane fiber content can be designed.

Selection of empirical coefficient

In order to select appropriate empirical coefficient in the compaction model, compressive experiments of the needle-punched preforms were carried out. The thickness change of the needle-punched preforms with pressure was collected by compressive experiment. The specimen size of the needle-punched preforms was 18 mm × 18 mm × 13.5 mm, as shown in Fig. 8a. The whole preform specimen was prepared by needling process with 13 mm needling depth, six rows of needle arrangements, and 12 mm stepped size. The fiber content each layer in the preform was the same. The surface density of short-cut fiber net was 140 g/m², and the thickness of net was 0.8 mm by measurement. The volume of needle-punched fiber accounted for 4.18% of the net fiber, which was

calculated by needle-punched fiber content analysis model. The compressive experiment was conducted on an Instron-2519 test machine as shown in Fig. 8b. The load and displacement in the compressive experiment were collected. The thickness changes of the needle-punched preforms with pressure were calculated through the theoretical compaction model and the compressive experiment.

Through the compaction experiment of the needle-punched preform, it is found that the thickness of the specimen gradually decreases with the increase of the compressive stress on the preform, and the curve of fabric stress variation with the thickness of the specimen can also be divided into three parts: the initial linear stage, the nonlinear stage and the final linear stage, as shown in Fig. 9. In the initial linear stage, the structure of the needle-punched preform is fluffy and the internal pores are large. The small compression load can make the fibers fit together quickly. The pores are reduced rapidly, resulting in
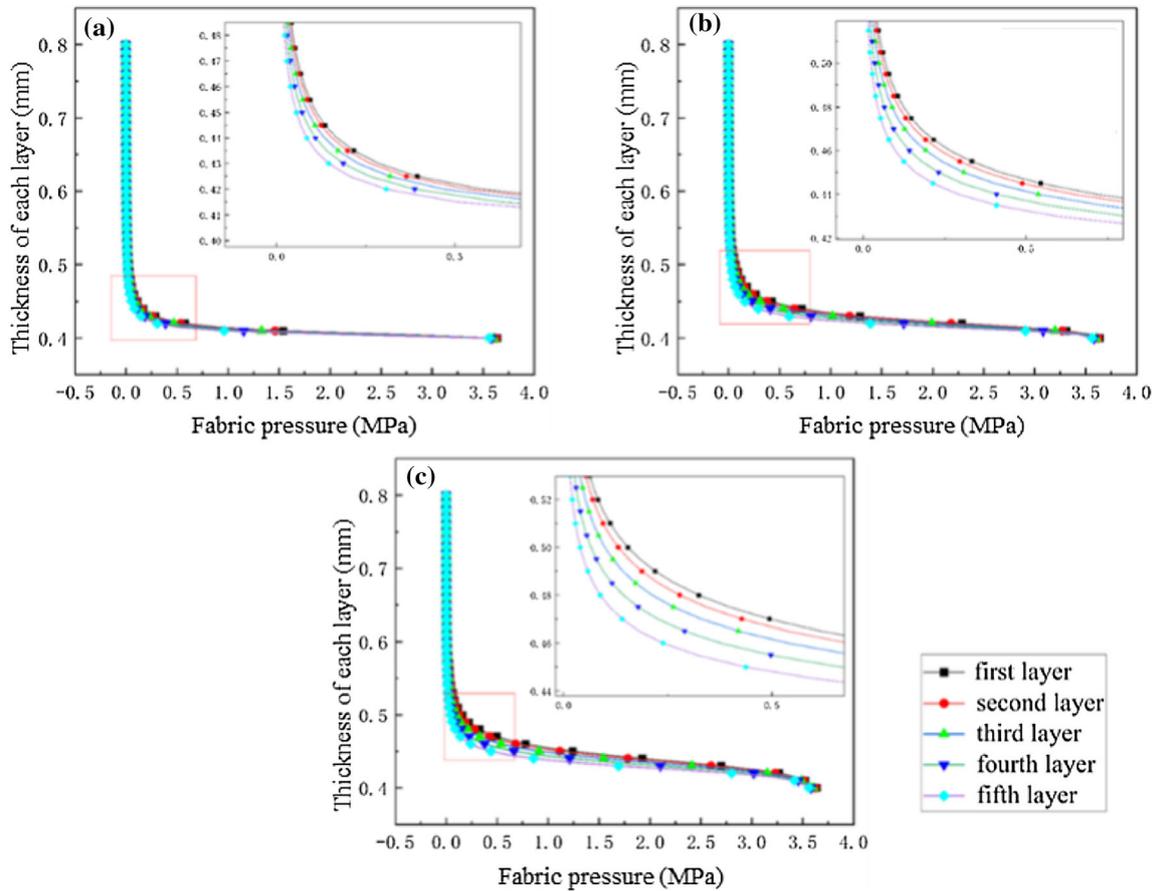
Figure 7 Pressure of different empirical coefficients changing with thickness, **a** Empirical coefficient $k = 2$, **b** Empirical coefficient $k = 3$, **c** Empirical coefficient $k = 4$.

Table 5 Parameters in the theoretical compaction model

Variable name	K_s (GPa)	T_0 (mm)	T_f (mm)	s_0 (%)	S_a (mm^2)	C_{b0} (MPa^{-1})
Value	13.2	0.8	0.4	9.83	6400	72.28

Table 6 Thickness and fiber content of fiber net after compaction

Layer	Thickness of fiber net (mm)			In-plane fiber content of fiber net		
	$k = 2$	$k = 3$	$k = 4$	$k = 2$	$k = 3$	$k = 4$
1	0.415	0.435	0.455	17.79%	17.01%	16.22%
2	0.413	0.433	0.453	17.30%	16.51%	15.73%
3	0.412	0.430	0.450	16.41%	15.73%	15.04%
4	0.411	0.427	0.443	15.33%	14.75%	14.25%
5	0.409	0.423	0.437	14.45%	13.96%	13.47%

the reduction in thickness. In the nonlinear stage, with the increase of compressive stress, the fibers in the preform fit closely, and the preform gradually reaches the compact state. In the final linear stage, the fibers inside the preform constantly squeeze each other. The fiber cross-sectional shape changes, and

the pores inside the preform are very small. The preform is difficult to be compacted again. It has similar experiment phenomena and rules with the previous studies [17, 18].

When the empirical coefficient $k = 2$, the calculated results of the compaction model are well consistent

(a)   **(b)**
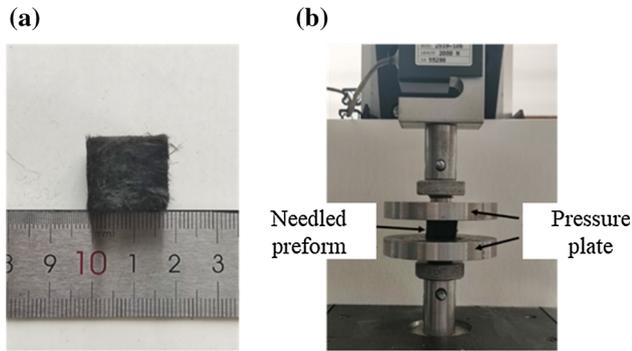
Figure 8 Compression experiment of the needle-punched preforms, **a** Compressive specimen, **b** Experiment fixture.
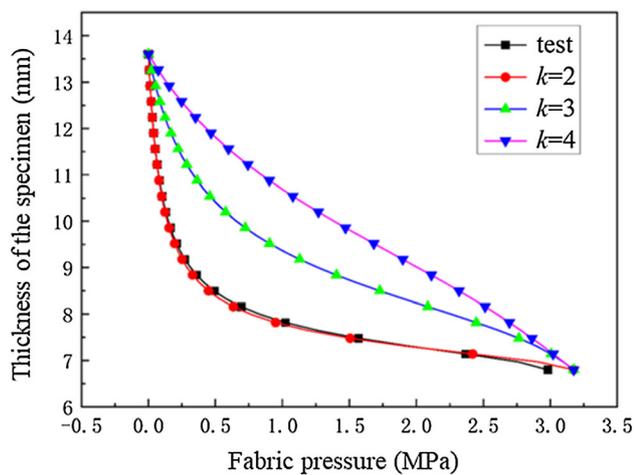
Figure 9 Relationship between the thickness of needle-punched preforms and pressure.

with the experimental curve as shown in Fig. 9. The maximum relative error in the nonlinear stage is 3.49%. Thus, the empirical coefficient should be $k = 2$ during the compaction process design of needle-punched preform with these material parameters. It is also proved that the theoretical model established in this paper is accurate and effective.

Design the fabric pressure based on compaction model

The thickness change of each layer during compaction should be designed which can be achieved by controlling the pressure of the needle plate in order to make the fiber content gradient. The relationship between the final fiber content in fiber net and the remaining fiber content after needling can be expressed as

Table 7 Fabric pressure and thickness of fiber net after compaction

Net number	Fabric pressure design value (MPa)	Net thickness design value (mm)	Net density before compaction (g/cm³)	Net density after compaction (g/cm³)
1	1.540	0.410	0.164	0.320
2	0.535	0.420	0.159	0.302
3	0.439	0.422	0.150	0.283
4	0.363	0.421	0.140	0.266
5	0.287	0.421	0.131	0.249

$$s_f = \frac{T_0}{T_f} s_r \qquad (13)$$

where s_f is the final fiber content and s_r is the remaining fiber content. For example, the fabric pressure of 5-layer fiber net is designed to make the fiber content become 18%, 17%, 16%, 15% and 14%, respectively, after compaction in this paper. The fabric pressure and the thickness of each fiber net layer are shown in Table 7. Thus, by setting the fiber content of each fiber net layer, the thickness of each layer in needle-punched preforms can be calculated and the fabric pressure of each layer can be designed. The density of the fiber net after compaction can also be obtained.

Conclusion

In this paper, the short-cut fiber net and the needle are modeled geometrically, and the process of the needle grabbing fibers is simulated. The correlation between the needling processes and the fiber content in layers is established. Based on the neural network, the design of variable density needled preforms is realized. At the same time, the compaction model of the needle-punched preform is established, and the change rule of the compaction rate and compression stress with the thickness of the fiber net is analyzed. The compression stress of the fiber net in the preform is designed, so that the fiber content of different fiber net can meet the gradient change requirements. The conclusions of this paper are as follows:

(1) A theoretical analytical method of z-direction fiber content is proposed. The result shows the number of fibers grabbed by needles is discrete

and uncertain. The probability distribution of the percentage of grasping fiber can be random. Using this method and the ANN model, the needling process is designed. The fiber content calculated is basically consistent with the design target value and the maximum relative error is 1.18%.

(2) A compacting model of needled preform is established. The thickness of the preform decreases gradually with the decrease of the compaction rate, but the fabric pressure will increase. And the thickness can be accurately obtained by controlling the pressure of needle plate. The relationship between the pressure and the thickness of the preform obtained by compression test is in good agreement with the calculated results of the compaction model. The maximum error between them is 3.49%. This work can provide strong theoretical guidance for material design and engineering production of variable density needle-punched preforms.

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Declarations

Conflict of interest　No conflict of interest exits in the submission of this manuscript, and all the authors listed have approved the manuscript that is enclosed.

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