Study on the Distribution of Frictional Forces on Z-Yarn Continuous Implanted Preforms and Its Application

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Title page

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Abstract: In order to improve the quality and efficiency of the Z-directional 3D preform forming, the Z-yarn friction force distribution model of the preform and its wear mechanism were investigated. Designed the tensile force measuring device of the replacement guide sleeves,the measured tensile force is equivalent to the Z-yarn friction force. Found that the frictional force was proportional to the number of preform layers, the frictional force applied to the one preform decreased from the corner, edge, sub-edge and middle in order. Established BP neural network model to predict the friction at different positions of preform with different layers, the error is within1.9%. The wear of Z-yarn was studied at different frictional positions and after different times of successive implantation into the preform, showed that with the increase of the number of Z-yarn implantation and the friction force, the amount of carbon fiber bundle hairiness gradually increase, and the tensile fracture strength damage of the fiber is increasingly affected by the friction force,and in the corner position of the preform, when the number of implantation is 25 times, the fiber fracture strength will occur non-linearly and substantially decreased, in order to avoid fiber fracture in the implantation process, the Z-yarn needs to be replaced in time after 20~25 times of continuous implantation.

Key words: Z-yarn implantation; BP neural network; Z-yarn wear

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1 Introduction

Advanced composite materials are widely used in the fields of aerospace, defense and military, rail transportation, etc, which are contested by industrially developed countries as strategic must-have resources. C/C composites with excellent high-temperature performance are widely used in missile warheads and solid rocket engine nozzles, aircraft brake discs, space shuttle structural components and other aspects[1]. The carbon fiber preform is the most basic reinforcing structural body of C/C composites, which can determine the volume content of fibers and fiber orientation, influence the pore geometry, distribution of pores and the degree of fiber bending and twisting in the composites, and determine the performance of the composites. C/C composites are always have been a hot spot for research in the industry[2-4].

Three-dimensional (3D) preform contains load-bearing fibers in all directions, solving the shortcomings of two-dimensional (2D) preform interlayer performance is insufficient, easy to damage, has better load-bearing performance, has been more attention and application of the current needling process for complex fiber structure will lead to preform damage and difficult to describe, macroscopic mechanical behavior there is a large dispersion[5]. 3D woven composites have complex structures, long process cycles, and are expensive to develop by traditional design methods[6], and weaving of complex curved components is also a difficult task. The overall degree of automation of woven molded preforms is still not high enough to meet the demand for short-time high-volume production[7], which also restricts the

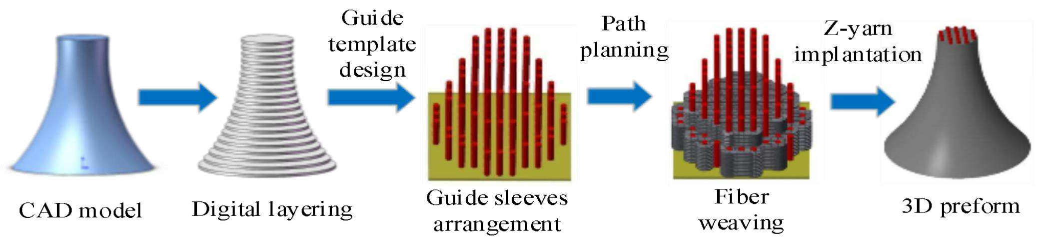


Figure 1 Digital weaving forming

development and application of 3D woven fabrics to a certain extent.

The digital 3D weaving and forming proposed by Shan[8], as shown in Figure 1, uses a layered weaving method with digital templates, which can realize the weaving and forming of complex preform by creating and forming structural parts along the digitally guided templates with fibers under computer control.

Using CAD to generate the model of the preform to be woven, using the arrangement of the guide sleeves to limit the shape of the preform to achieve, the forming process of the composite preform will first lay the fiber bundles in the X and Y directions between the guide template layer by layer, using the side bar and guide sleeve to restrain the shape of the fiber position, laying to a certain thickness for compaction densification, repeat the above steps to complete the weaving of the preform, as shown in Figure 2.

After weaving, the Z-yarn need to be inserted into the preform to replace the guide sleeve, as shown in Figure 3. First, a steel needle (called a replacement needle) carrying the Z-yarn is used to position the needle at the coaxial point of the guide sleeve, as in Figure 3(a), and move forward along the guide sleeve to replace the guide sleeve while introducing the Z-yarn into the preform, as in Figure 3(b), after replacing the first guide sleeve, the second guide sleeve is replaced in the opposite direction, as in Figure 3(c), and the Z-yarn is implanted into the preform again as in Figure 3(d). Repeatedly replacing the entire guide sleeve with the replacement needle carrying the Z-yarn into the preform, forming a three-dimensional preform finally. About research on Z-yarn, Hassan[9] showed that the accurate design of the Z-yarn path and more importantly, its frequency in a three-dimensional woven structure is essential for impact-resistant composite structures. Midani[10] found changing the number of Z-yarn in the structure have a negligible effect on tensile (in-plane) and a significant effect on weight reduction impact performance (out-of-plane). Abdel[11] designed a generic geometric model to represent the structure of Z-yarn by means of the values of knitting coefficient, yarn material bulk density, knitting coefficient, yarn material bulk density, yarn packing factor, yarn size, yarn linear density, yarn spacing and number of Y-yarn plies. K[12] pointed out that the root cause of the structural instability of the preform is the thickness variation, where the main factors are the width ratio of the preform and the introduction path of Z-yarn fibers. Xu[13] pointed out that interlayer intercut strength of out 3D needled SiC increases with increasing yarn size and Z-yarn density and decreases with yarn size and Z-yarn density. Scholars have only pointed out the importance of Z-yarn for preforms and composites, but the distribution pattern of the frictional forces to which Z-yarn is implanted in preforms has not been studied

Regarding the friction studies of fibers, Yang[14] found that the degree of wear of carbon fiber bundles increases with the increase of the normal load F, leading to a decrease in the mechanical properties of the yarn, and fiber damage leads to a substantial decrease in the tensile properties of the fabric. Allaoui[15] found that the relative orientation of the yarns in the fabric had a significant effect on the coefficient of friction and that the coefficient of friction of the fabric increased with the increase in warp and weft density. Tourlonias[16] found a decreasing trend in the coefficient of friction and its coefficient of variation of carbon fiber bundles as the degree of pulp film wear between the filaments increased. Cornelissen[17] explored the relationship between carbon fiber bundles and the friction properties of fabrics at three scales, microscopic, fine and macroscopic, predicting the friction pattern between satin fabrics woven from fiber bundles and metals by

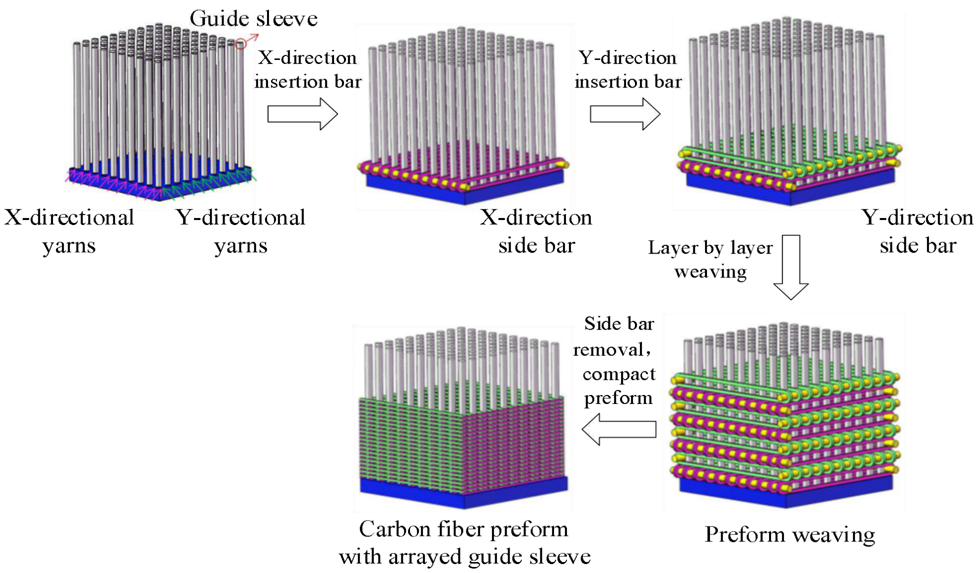


Figure 2 Composite preform weaving

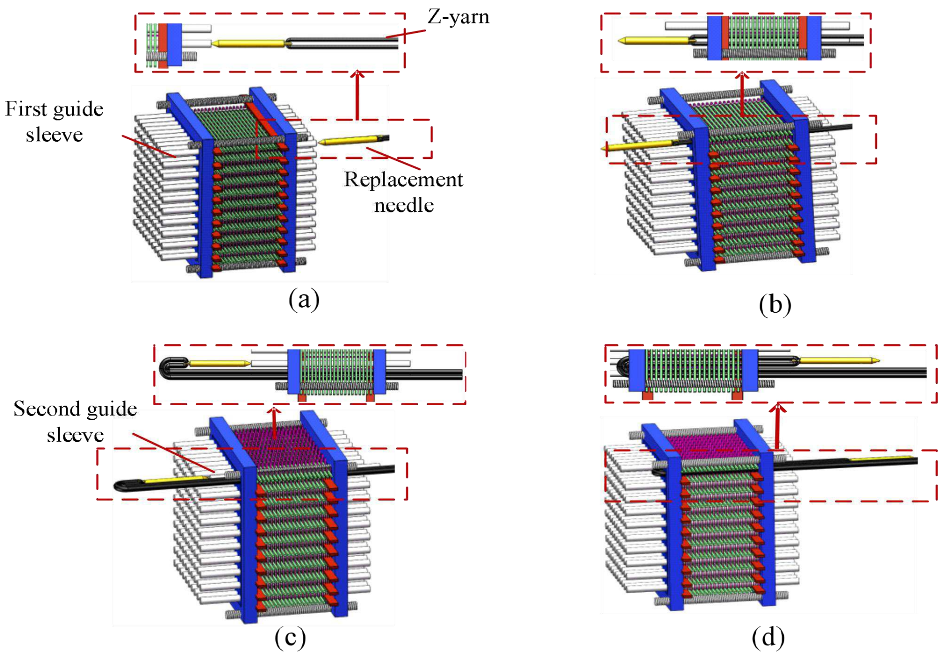


Figure 3 Z-yarn replacement guide sleeve

observing the friction pattern between the bundles and metals. Lee[18] found that damage to carbon fiber bundles during weaving was caused by abrasion of fiber bundles by guide rods. Archer[19] found that the overall damage caused by weaving to carbon fiber bundles decreased the tensile fracture strength of carbon fiber bundles by 9% to 10%, which is much lower than the performance damage caused by weaving to glass fiber bundles. Yoshiki[20] designed a device to evaluate the dynamic friction between carbon fibers and found that the state of the cladding between the filaments was strongly influenced by the compressive stress, and also has a significant effect on the coefficient of dynamic friction of the fiber.

The current research on fiber friction has revealed the damage mechanism of fibers and also studied the fiber wear in X, Y direction during the weaving process, however, there is no research on the change of damage of Z-yarn after implantation into the precast and when Z-yarn need to be replaced to prevent them from breaking in the precast due to high wear.

In this paper, a homemade tensile force measuring device is used to measure the preform

Figure 4 Z-yarn implantation condition

of different thicknesses. The force required to replace the guide sleeve in different positions is expressed as F, F is equivalent to the frictional force on the Z-yarn implanted preform, and obtained the distribution pattern of F in the preform. Modeling the distribution of frictional forces on Z-yarn implantation of preform with different thicknesses by Bp neural network, enables prediction of frictional forces on large and complex preform with Z-yarn; experiments of continuous replacement of guide sleeves with Z-yarn were done for different frictional regions. By tensile testing and checking the amount of hairiness on the fiber bundle surface, detecting the amount of hairiness on the fiber bundle surface, the relationship between the wear of Z-yarn in the preform and the number of preform layers, the position of the guide sleeve, and the number of replacement guide sleeve was obtained to solve the situation of low preform forming efficiency and poor quality, as shown in Figure 4. To improve the theoretical basis and practical process data for the realization of continuous Z-yarn implantation.

2 Experimental materials and methods

2.1 Prefabricated system preparation

Toray T300 series 3K carbon fiber tow was selected to complete the weaving of the preform of the flexible-guided three-dimensional structural composite member, according to the flexible guided 3D weaving technology[8].

Guide sleeves are introduced in the thickness direction of the composite preform, which outline the preform and achieve near-net forming, and the guide sleeves lock forming, and the guide sleeves lock the fibers woven in layers to provide Z-directional reinforcement. Since the guide sleeves are pre-positioned on the weaving guide template, the fibers are woven according to a defined path to the guide sleeves position when the guide sleeve are locked according to a defined locking pattern, taking advantage of the maximum advantage that the guide sleeve can bring[21].

The Z-yarn are implanted into the preform after weaving is completed and the guide sleeves are replaced. In the weaving surface, 3K fiber bundles are wound by 0° /90° guide sleeves in X and Y directions respectively, where orthogonal winding is done once, which is defined as one weaving layer, and 50, 100, 150, 200 and 250 layers of carbon fiber preforms with thicknesses of 25mm, 50mm, 75mm, 100mm and 125mm are woven respectively. After weaving, two 6K fiber bundles are implanted into the preform member from the Z direction to complete the in-situ replacement of the Z-yarn to the guide sleeves, so as to realize the overall restraint and reinforcement of the preform of composite components.

2.2 Yarn replacement force measurement method

The tension measuring device was designed to replace the guide sleeve for the structural characteristics of the guide sleeves, and the gripper was connected to the sensor on one side and the guide sleeve on the other side, and the required replacement force was fed back to the sensor by dragging the guide sleeve outward, and the replacement force value was displayed on the computer through digital module processing, as shown in Figure 5. Since the weaving process is repetitive and the preform has a rectangular cross-section with axial symmetric characteristics, only 1/4 of the preform cross-section is considered for the study, and each guide sleeve of the preform is taken separately for the yarn replacement force measurement.

Since the tensile force measurement of the replacement guide sleeves(RGST) has the factors of many data and high volatility, the experiment to verify the accuracy of tensile force measurement was first done with a preform of

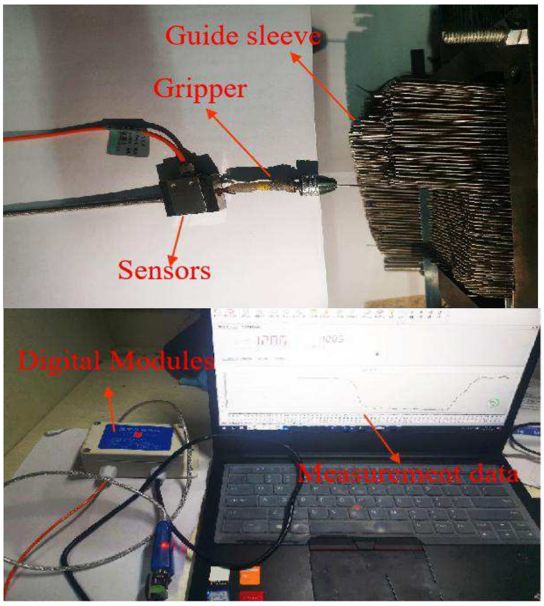
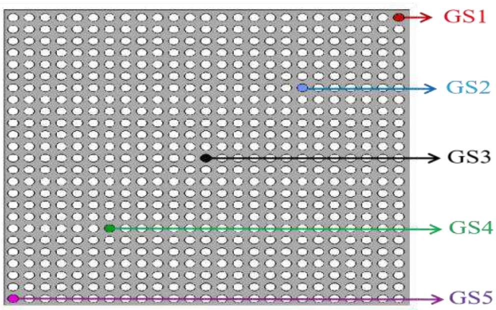


Figure 5 Yarn tying force measurement device

50 layers and 25 mm thickness. In order to ensure the universality of the results, the diagonal position of the guide sleeves were divided into four parts, and five guide sleeve GS1, GS2, GS3, GS4 and GS5 were taken at the end point for RGST measurement. The RGST were measured five times for the same guide sleeve, as shown in Figure 6. The maximum error of the yarn replacement force is 5.2%, which shows that the fluctuation and error of the measured yarn replacement force are within the acceptable range and can be used to accurately measure the size of the replacement force of the preform.



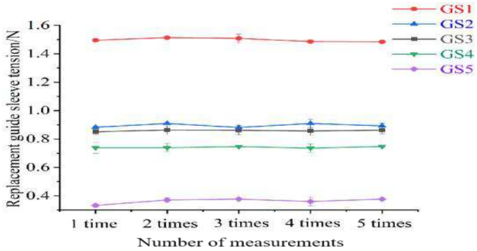
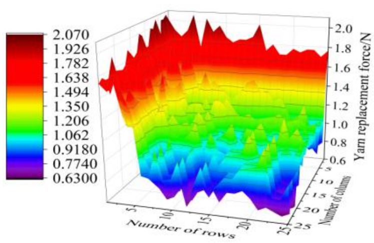


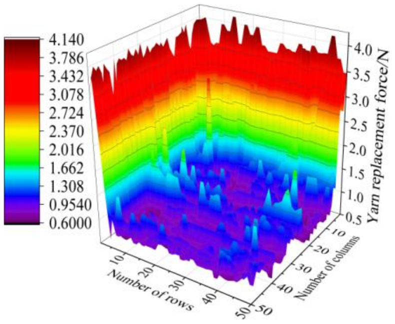
Figure 6 Tensile force measurement of the replacement guide sleeve fluctuations

3 Experimental results and analysis

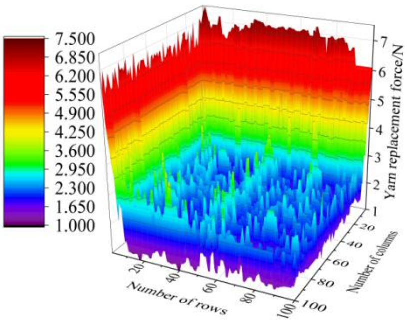
The preform of flexible guided three-dimensional weaving consists of in-plane X-direction yarn, in-plane Y-direction yarn and Z-directed guide sleeve respectively before Z-yarn implantation. The diameter of the guide array is 1.2 mm and the center spacing is 2.4 mm. After preform weaved, the Z-yarn is used to replace the guide sleeves to form the flexible guided three-dimensional woven preform. Hu[21] found that the fiber volume content of the flexible-guided three-dimensional woven preform increased with increasing compressive stress, and the fiber volume fraction changed more and faster when the preform was compacted when the number of woven layers was small, and the growth trend gradually leveled off as the number of woven layers increased. The higher fiber volume fraction indicates the better denseness of the preform, that is, the higher force required for Z-directed guide sleeves replacement. During the compaction process of the preform, the fiber bundles and the guide sleeves squeeze each other to produce small deformations, and the guide sleeves at different locations are subjected to different forces. Therefore, the replacement force of the guide sleeves at different positions of the 50, 100, 150, 200, and 250 layers preforms were measured using the device to measure the replacement force, and the results were shown in Figure 7.



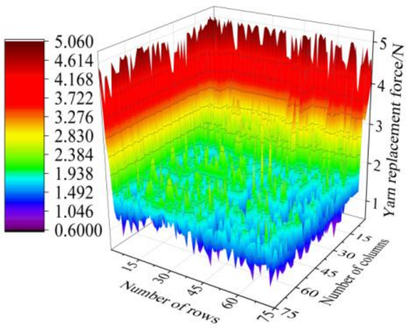
(a)50 layers



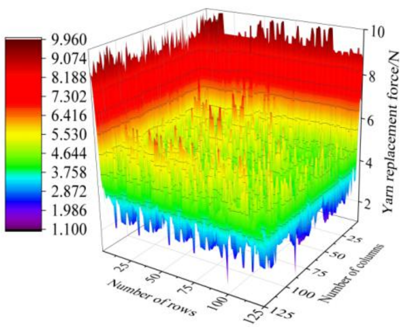
(b)100 layers



(c)150 layers



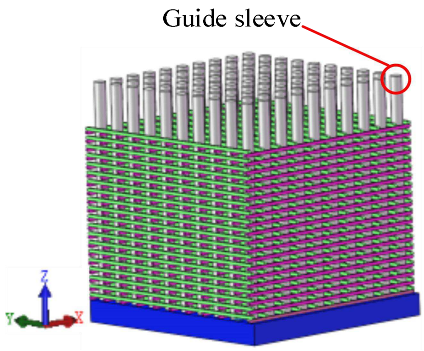
(d)200 layers



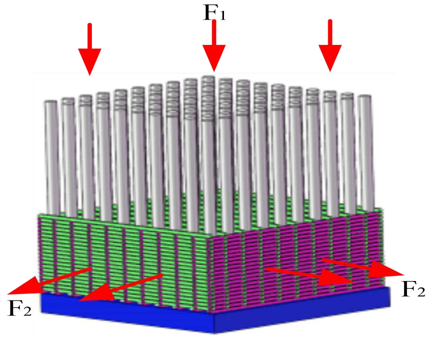
(e)250 layers

Figure 7 Yarn replacement force distribution

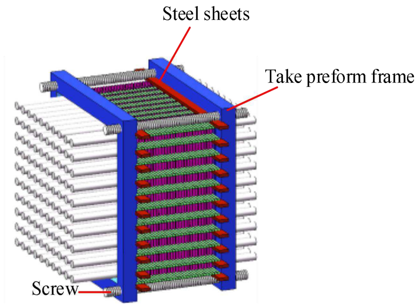
From Figure 7(a)~(e), it can be seen that by measuring the force F required to replace the guide sleeve of the five preforms, the maximum value of the force F required to replace the guide sleeve is proportional to the thickness of the fabric, and for the same fabric, the F value decreases from the corner, edge, secondary edge, and central part in order. This is due to the digital flexible guide preform forming process to ensure the fiber volume fraction of the fabric, it is necessary to apply positive pressure F1 on the preform, the height of the preform Z direction is reduced, due to the volume of the same, its X, Y direction length will increase, however, the guide sleeves limit its displacement in X and Y directions, so the fiber in the X, Y direction will have a force F2 with the guide sleeves, as in Figure 8 (a), 8 (b), resulting in the lowest value of F at the center of the fabric, and the closer the distance to the outermost guide sleeves, the higher the F value. In addition, after the preform weaving is completed, it needs to be removed from the table, first insert the steel piece into the gap between the two adjacent rows of the guide sleeve, and then insert the steel piece into the gap of the pickup frame at the same time to complete the position of the pickup frame and the preform fixed. Finally, adjust the distance between the two taking frames to adjust the thickness of the preform to a suitable position, as shown in Figure 8(c). Adjustment of the distance between the pickup frame needs to be completed by the screw, so the corner part of the fabric has the largest deformation of the pickup frame, that is, the outermost corner part of the fabric has the largest force value with the guide sleeves.



(a)



(b)



(c)

Figure 8 Force on guide sleeve

4 Replacement yarn force distribution modeling of preform

Error back propagation (BP) neural networks have a simple structure and can be trained to automatically summarize the functional relationships between data without any a priori formulas, and thus have advantages that traditional mechanical or mathematical methods cannot match[22], and are widely used in financial, biological, medical, health, and marketing research fields[23]. Liu[24] proposed a back propagation artificial neural network (BP -ANN) model to predict the body dimensions related to pattern making by inputting several key body dimensions. Haoran Liu[25] optimized the BP neural network with an improved genetic algorithm to derive the optimal weight gaps. The improved network improved the convergence performance, saved the running time and reduced the mean square error. The application of BP neural network to model the replacement force of preform is of great importance for the continuous dynamic prediction of the replacement force of preform with different layers at different positions.

4.1 BP network modeling

The feedforward network of its learning algorithm is first established, which consists of an input layer, an implicit layer, and an output layer[26]. The BP learning algorithm consists of two parts: forward propagation of information and backward propagation of errors. In the forward propagation process, the input information is computed from the input to the output layer by layer through the implicit layer, and the state of neurons in each layer only affects the state of neurons in the next layer[27]. If the desired output is not obtained at the output layer, the value of the error change at the output layer is calculated and then shifted to back propagation, where the error signal is back propagated through the network along the original connection pathway to modify the weights of the neurons in each layer until the desired goal is reached[28]. The configuration of the input layer needs to take into account all the elements that affect the output layer, which is the result of the model analysis that is the replacement force, so for this system the input layer mainly includes the number of preform layers, the number of array steel needle columns, and the number of array steel needle rows.

The selection of the implied nodes is based on the correct reflection of the input and output, and the number of implied nodes is chosen as less as possible. Then it is gradually increased during training according to the situation until the network performance requirements are met. The initial value of the number of hidden nodes is determined by the Eq.(1) [29].

$$n = \sqrt{n_i + n_0} + a \tag{1}$$

where n is the number of hidden layer nodes, ni is the number of input nodes, n0 is the number of output nodes, and a is a constant between 1 and 10.

In this study, according to the number of input and output nodes and the smallest possible value, the implicit nodes are initially selected as 5~14. The network is trained for different implicit layers, and the analysis of the predicted regression coefficient Regression with the number of hidden nodes n is shown in Figure 9. The more the regression coefficient tends to 1, the best fitting effect is achieved, so the best implicit layer node number is finally selected as 9.

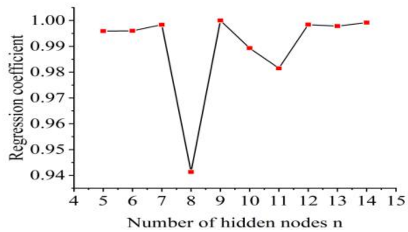


Figure 9 Relationship between hidden points and regression coefficients

The structure of the feedforward neural network is shown in Figure 10.

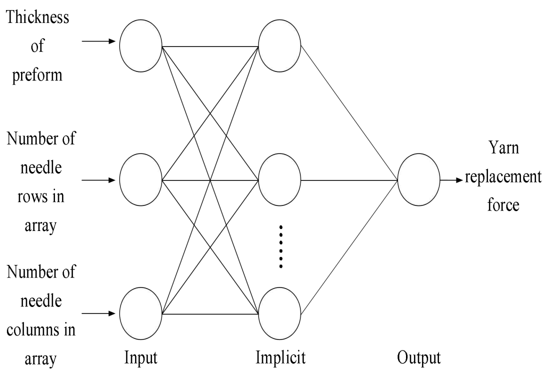


Figure 10 BP neural network model for cutting force prediction

MATLAB provides a variety of improved neural network tool functions, this study selects the fast BP algorithm to train the forward network, which is a method using a combination of momentum and adaptive learning rate, BP algorithms mainly include Levenberg-Marquardt algorithm, Bayesian Regularization algorithm, Scaled Conjugate Gradient algorithm, selected different algorithms under the same conditions, the network is trained, the results are compared and analyzed, and the mean square error is selected as the criterion for algorithm selection, as shown in Table 1.

Table 1 Comparison of the effect of different BP training

Training algorithms	Mean Square Error		
	Training	Validation	Testing
Levenberg-Marquardt	$2.244e^{-4}$	$2.708e^{-2}$	$2.706e^{-2}$
Bayesian Regularization	$5.431e^{-4}$	$7.2553e^{-4}$	$6.954e^{-4}$
Scaled Conjugate Gradient	$5.617e^{-1}$	$1.897e^{-1}$	$1.514e^{-0}$

According to the run results, the Bayesian Regularization algorithm has the smallest mean square error and is the most stable, so it is chosen as the training algorithm for the replacement yarn force distribution model.

When designing a BP neural network, it is necessary to determine the topology of the network (the number of layers of the hidden layers and the number of neurons in each layer) and the transformation function of its neurons, the initialization of the network, error calculation, learning rules and network training, training parameters and normalization of training samples, etc. MATLAB Neural Net Fitting Tool includes important excitation functions, such as nonlinear functions and the Sigmoid linear function type used in this paper, etc, as well as the neural network structure, the number of neurons set, and also according to their own needs to call the neural network in the toolbox, modify the network connection weights and threshold rules, write a variety of network training procedures to achieve a variety of desired functions[30].

4.2 Network training and result analysis

The training of the neural network of the replacement yarn model consists mainly of, three neuron inputs: x_1 = number of preform layers, x_2 = number of rows of array stitches, x_3 = number of columns of array stitches, which are connected to three weights (w_1, w_2, w_3) of the weighting ratio of the weight adjustment inputs. Selecting the most efficient linear weighted summation yields the Net_{in} neuron net input Eq.(2).

$$Net_{in} = \sum_{i=1}^{n} w_3 * x_3 \qquad (2)$$

The activation function is chosen as the Sigmoid function, which transforms the input from negative infinity to positive infinity into an output between 0 and 1. If there is no constraint, a linear activation function (the sum of the multiplication of the weights) can be used, yielding an output of the Eq. (3).

$$y = sigmoid(\sum_{i=1}^{n} w_3 * x_3) \qquad (3)$$

The Sigmoid function is defined in the equation of Eq.(4).

$$sigmoid(x) = \frac{1}{1+e^{-x}} \qquad (4)$$

Substituting Eq.(4) into Eq.(3) yields Eq. (5).

$$y = \frac{1}{1+e^{-Net_{in}}} \qquad (5)$$

The logical model of the training threshold of the substitution force network is shown in Figure 11.

As shown in Figure 10, the three nodes in the input layer are numbered 1, 2, 3, the hidden

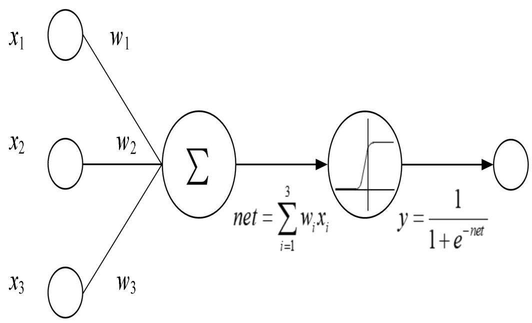


Figure 11 Sigmoid threshold unit model

layer has nine nodes, numbered 4~12 in order, the output layer has one node, numbered 13. The data are analyzed using the yarn force data of different positions of 50, 100 and 150 layers of prefabricated bodies as samples, and the input and output matrices are established as 222*75, 1*75 respectively. According to the values of nodes 1, 2, 3 values and Eq.(3), the output values of node 4 can be obtained as Eq.(6).

$$a_4 = sigmoid(\sum_{i=1}^{n} w_3 * x_3) = sigmoid(w_{41}x_1 + w_{42}x_2 + w_{43}x_3) \tag{6}$$

where w_{41}, w_{42}, w_{43} are the weights of nodes 1, 2, 3 to node 4 respectively, and similarly the output values of nodes 5 to 12 can be calculated, so that the 9 values of the hidden nodes can be calculated. Define the network input vector and weight vector of each node in the hidden layer, order:

$$\vec{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ 1 \end{bmatrix} \tag{7}$$

$$W = \begin{bmatrix} \overrightarrow{w_4} \\ \overrightarrow{w_5} \\ \overrightarrow{w_6} \\ \vdots \\ \overrightarrow{w_{12}} \end{bmatrix} = \begin{bmatrix} w_{41}, w_{42}, w_{43} \\ w_{51}, w_{52}, w_{53} \\ w_{61}, w_{62}, w_{63} \\ \vdots \\ w_{121}, w_{122}, w_{123} \end{bmatrix} \tag{8}$$

$$\vec{a} = \begin{bmatrix} a_4 \\ a_5 \\ a_6 \\ \vdots \\ a_{12} \end{bmatrix} \tag{9}$$

Combining Eq.(6), Eq.(7), Eq.(8) and Eq.(9) yields Eq.(10).

$$\vec{a} = sigmoid(W \bullet \vec{x}) \tag{10}$$

Since the algorithm of each layer is the same, for the alternative yarn force distribution network model with 3 input layers, 1 output layer and 9 hidden layers, assume that the weight matrices are W_1, W_2, W_3...W_9, each hidden output is $\overrightarrow{a_1}$, $\overrightarrow{a_2}$, $\overrightarrow{a_3}$, and the input of the neural network is $\vec{x}$, and the output of the neural network is y, then the output vector of each layer can be computed and expressed as Eq.(11).

$$\begin{aligned} \overrightarrow{a_1} &= sigmoid(W_1 \bullet \vec{x}) \\ \overrightarrow{a_2} &= sigmoid(W_2 \bullet \overrightarrow{a_1}) \\ \overrightarrow{a_3} &= sigmoid(W_3 \bullet \overrightarrow{a_2}) \\ &\vdots \\ y &= sigmoid(W_{12} \bullet \overrightarrow{a_{11}}) \end{aligned} \tag{11}$$

Then the input data will be normalized by the mapminmax function to get input, output, and the normalization function is set as in Eq. (12).

$$y' = 2\frac{x_n - x_{\min}}{x_{\max} - x_{\min}} - 1 \tag{12}$$

The inverse normalization function is set to the Eq. (13).

$$x_n = y' \bullet (x_{\max} - x_{\min}) + x_{\min} \tag{13}$$

Where x_n is the nth input data, x_{max} is the maximum value of the input data, x_{min} is the minimum value of the input data, and y' is the nth normalized data. After the results are obtained and then reverse normalized to find out the magnitude of the yarn replacement force at different positions, the fit of the test sample is shown in Figure 12.

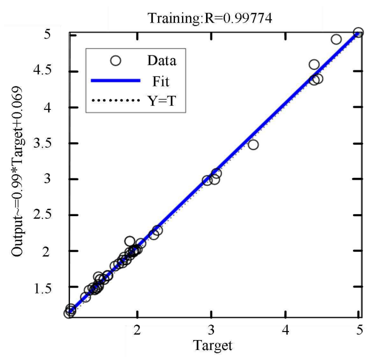


Figure 12 Bayesian network training sample fit

The mean square error of the training set, validation set, test set and overall with the number of training is shown in Figure 13.

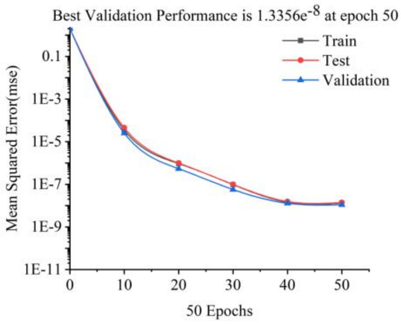


Figure 13 Neural network Performance fit

It can be seen that the accuracy of this fitting is very high, and the number of training is completed at 50 times with a mean square error of $1.3356e^{-8}$, without the phenomenon of overfitting. After establishing the replacement force distribution model, the myNeuralNetworkFunction(x) neural network function in MATLAB was used to predict the required replacement force magnitude by inputting the number of preform layers, the number of array steel of steel pins rows, and the number of array steel of steel pins columns in x respectively, through the ans value of the neural network. To further verify the accuracy of the model, the values of yarn replacement force were predicted for 200 and 250 layers of the preform with different number of rows and columns, respectively, and the errors between the predicted and actual values for different guide sleeve positions are shown in Figure 14.

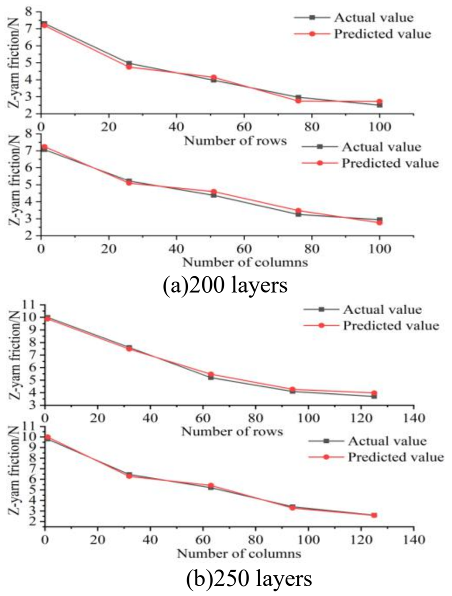


Figure 14 Fitting of preform with different layers and different positions

The above results show that the simulated value of the BP network model for predicting the yarn replacement force fits well with the actual value, and the more layers of the preform, the greater the yarn replacement force, the better the fitting effect is, and the maximum error is 1.9%, which is of great practical significance to find out the size of the yarn replacement force at different layers and different positions of the preform.

5 Z-yarn strength factor analysis

The shear resistance of carbon fiber is poor, and it is easy to cause wear of carbon fiber in the process of implanting the preform, which shows that the fiber surface is rough or even broken, which will lead to the interruption of the process of continuous implantation of carbon fiber and reduce the forming efficiency of the preform, and also make the volume fraction of Z-yarn of the preform decrease, which greatly affects the overall mechanical properties of the preform.

Combined with the prediction model of yarn replacement force distribution derived from the previous section, the 150 layers preform was selected as the experimental object, and six positions with replacement forces of 1.75N, 2N, 2.5N, 3N, 3.5N, 4N were selected to replace the guide sleeve 5, 10, 15, 20, 25 times with two 6K carbon fiber bundles from Toray of Japan as the Z-yarn, the replacement speed was 5mm/s, and the Z-yarn moves distance is 75mm once. Z-yarn is glued to the reinforcement piece of 50mm in length and 10mm in width, and the length of fiber between the reinforcement pieces is 150mm, and the maximum breaking strength of Z fiber under different replacement times is tested by using a universal tensile testing machine, loading speed 1mm/min, as shown in Figure 15.

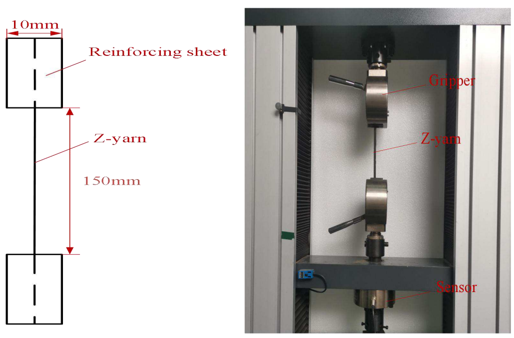
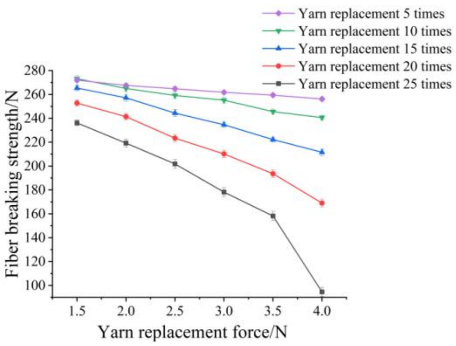
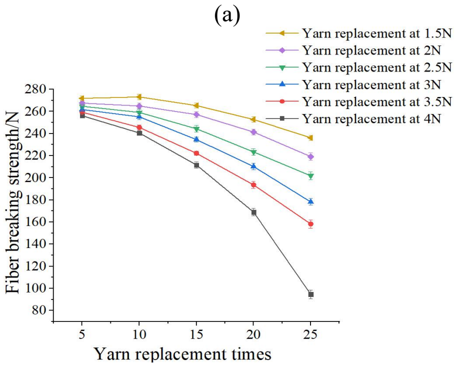


Figure 15 Z-yarn tensile strength test

The relationship between the number of different fiber replacements and fiber breaking strength of Z-yarn in the same position area of the preform was obtained, as shown in Figure 16(a); in the same number of replacements, the relationship between different position areas and fiber breaking strength was obtained, as shown in Figure 16(b).



(a)

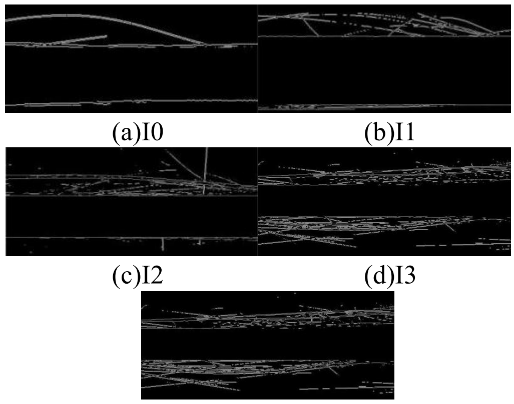


(b)

Figure 16 Fiber fracture strength as a function of preform position and friction number

From Figure 16(a), it can be seen that for the same preform area, as the number of yarn replacements of the guide sleeves increases, the breaking strength of the fibers becomes smaller, and from Figure 16(b), it can be seen that the greater the frictional force on the fibers in the Z direction, the more obvious the decrease in the breaking strength of the fibers as the number of replacements increases.And at the area where the friction force is 4N, the RGST of Z-yarn implanted for 25 times decreases substantially. The surface morphology of the Z-yarn with different implantation times is shown in Figure 17, and the hairiness area of the upper and lower parts of the dimensional bundle was selected and the average grayness value of the part of the area was calculated; the more the amount of hairiness, the greater the grayness value and the more severe the fiber wear[31].

From Figure 17(a), it can be seen that the



(a)I0 (b)I1

(c)I2 (d)I3

(e)I4

Figure17 Z-yarn surface hairiness at different implantation times

surface of the carbon fiber bundle is relatively smooth when the number of implantation is 5 times; with the increase of the number of implantation, as shown in Figure 17(b) to (e), the number of hairiness produced on its surface also increases. This is due to the fact that the more the number of implantations, the more frequent the mutual friction between the fibers inside the Z-yarn bundle and the X and Y-directional fibers in the preform, which causes a certain amount of hairiness on the surface of the carbon fiber bundle after the friction. Table 2 shows the statistics of the grayscale values of the hairiness of the samples under different implantation of Z-yarn. It can be seen that the number of hairiness of sample I4 is the most, followed by that of sample I3, and the number of hairiness of sample I0 is the least; only from the perspective of friction, the more hairiness, the more damage the carbon fiber bundle suffers, which is consistent with the variation of tensile properties.

Table 2 Statistics of hairy gray value of Z-yarn samples under different implantation times

Serial number	I0	I1	I2	I3	I4
Number of implantation	5	10	15	20	25
Grayscale value	96.203	97.510	98.424	99.543	101.862

Therefore, in order to avoid yarn breakage in the preform, which affects the strength of Z-yarn, it is necessary to replace the guide sleeve 20~25 times in the corner position of the preform, that is, when the Z-yarn are implanted in the preform at a distance of 1500mm~1875mm, the Z-yarn need to be replaced in time.

6 Conclusion

(1)The designed tensile force measuring device and sensors were used to accurately measure the size of the replacement force at different positions of the 50 layers, 100 layers, 150 layers, 200 layers and 250 layers carbon fiber preforms, revealing that the size of the replacement force of the carbon fiber preforms decreases from the corner, edge, secondary edge and central part in order.

(2)The number of preform layers, the number of guide sleeve rows and columns are used as input layers, and the replacement force is used as output layer, different algorithms were compared and the optimal genetic algorithm was selected for the 150-ply preform yarn force data, a model was developed to predict the distribution of replacement forces at different positions for preforms with different number of layers, the predicted value is within 1.9% of the actual error, effectively predicted the distribution of friction of prefabricated bodies with different thickness and number of layers.

(3)As the number of guide sleeve replacements increases in the Z-yarn, the tensile fracture strength of carbon fiber bundles is decreasing, the amount of hair and feathers gradually increases, this indicates a gradual increase in wear and tear; in the middle and the sub-edge position of the preform, Z-yarn tensile breaking strength loss is not significantly affected by the number of guide sleeve replacements, in the edge of the preform, the loss of Z-yarn tensile strength at break is influenced by the number of guide sleeve replacements with a significant linear decreasing trend, at the corner position of the preform, significant non-linear decrease in fiber tensile breaking strength, to avoid fiber breakage during implantation, when the Z-yarn replaced in the corner are 20~25 times, the Z-yarn need to be replaced in time.

7 Declaration

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Availability of data and materials
The datasets supporting the conclusions of this article are included within the article.

Authors' contributions
The author' contributions are as follows: was in charge of the whole trial; wrote the manuscript; experiment and analysis.

Competing interests
The authors declare no competing financial interests.

Consent for publication
Not applicable

Ethics approval and consent to participate
Not applicable

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