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Geometric Model for Multi-axial Warp-knitted Fabric Based on NURBS

Abstract
Based on studying the constitution of yarn system and the geometric modality of relevant yarns in the multi-axial warp-knitted structure, 3D solid models of the loop yarns, insertion yarns and chopped strand mat in modern multi-axial warp-knitted fabrics were built to reflect the geometric structures of the three items by using NURBS curves and the principle of curved surfaces. Besides, OpenGL was employed to explore the corresponding 3D computer simulation system under the condition of VC++.NET, which could simulate the geometric model of multi-axial warp-knitted fabric. Meanwhile, through the selection of the unit cell of the fabric, the unit cell model of modern multi-axial warp-knitted fabric with chopped strand mat was developed and the relation between geometric parameters and process variables was deduced. The theoretical fibre volume fraction formula of modern multi-axial warp-knitted fabric with chopped strand mat was obtained as well. Furthermore, by using different specifications of fabric as samples, theoretical and experimental values of the fibre volume fraction were compared. The results revealed that there was good agreement between the theoretical and experimental values, which proved that the model was scientific and practical.

Key words: *warp knitting, multi-axial, geometric model, 3D simulation, fibre volume fraction.*

Multi-axial warp knitting technology is an advanced knitting method which can bind multiple sets of parallel straight yarns together by stitching yarns. It has become the main technology to make the performs of composites. Multi-axial warp-knitted fabrics have many wonderful properties such as excellent formability, good impact resistance and high energy absorption. They have also been widely used in the fields of aerospace, wind power blades, transportation, construction, and so on [1]. According to the extensive application of multi-axial warp knitting composites, it is particularly important to undertake an in-depth study of the micro-structure of the fabric. The reason is that textile structure not only determines the volume content and direction of the fibre, but also impacts the geometry and distribution of the pore space, and even the deformation of the fibre in the composites [2]. Meanwhile, all the parameters above have a close relationship with the final performance of the composites. However, because of the limitation of the conditions, although many domestic and foreign scholars have in done certain researches on a geometric model of multi-axial warp-knitted fabric [3 - 7], those models cannot reflect the characteristics of the geometric structure of modern multi-axial warp-knitted fabric with a chopped strand nor guide the design and production of this fabric in practice.

In view of this situation, in this paper we built a 3D solid model of modern multi-axial warp-knitted fabric with chopped strand mat by using NURBS curves and the principle of curved surfaces. And then a 3D simulation system of multi-axial warp-knitted fabric was developed via VC++. NET and OpenGL which could simulate this kind of fabric. At the same time, the accuracy of the model was proven with the help of the fibre volume fraction, which was an important parameter. It is significant not only for speeding the design of multi-axial warp-knitted fabrics and improving the design accuracy of products, but also for shortening the development cycle of this fabric. Moreover this research also lays a concrete foundation for the further study of permeability, flow conductivity and micro-mechanical properties of composite reinforced material.

Structure features of multi-axial warp-knitted fabric

Multi-axial warp-knitted (referred to MWK) fabric is a kind of multi-layer fabric made up of multi-layer reinforced insertion yarns bound up by a chain, tricot or variable tricot texture. The fabrics can reach 8 layers (7 wefts, 1 warp) at most, and can also be added with chopped strand mat or fibre mesh. The fabric is composed of stitching, warp insertion (0°) and weft insertion yarns (± θ°). The angle θ of weft insertion yarns can be varied between 20 and 90º according to the usage of fabric. ***Figure 1*** shows a typical four-axial warp-knitted fabric structure. The direction of the four groups of insertion yarns are as follows: -45°/90°/+45°/0°, and the knitting structure is tricot texture. The structural features of MWK fabric are mainly as follows:
1) in the same production equipment, fabric density and insertion yarn angle can be adjusted;
2) as the insertion yarns are arranged completely parallel and straight, and the yarns of each layer are high ori-

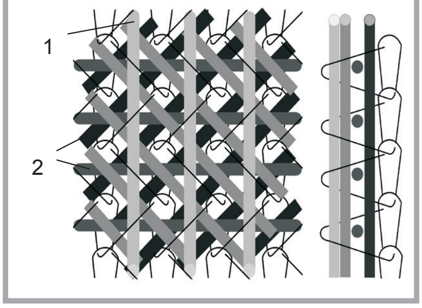

Figure 1. *Structure diagram of four-axial warp knitted fabric: 1 - warp insertion yarn 2- weft insertion yarn.*

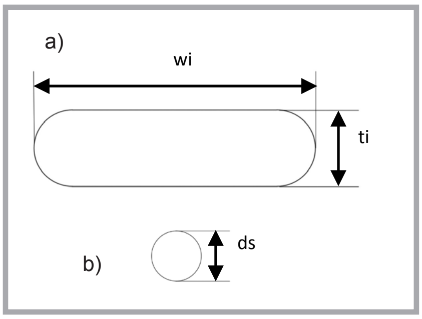

Figure 2. Cross section shape and size of yarns in the geometric model: a) cross section shape and size of insertion yarn, b) cross section shape and size of stitch yarn.

ented, the fabric has good mechanical properties;
3) the reinforced insertion yarns can reach 8 layers, and the integrity of the fabric is very excellent;
4) the fabric structure can be combined with chopped strand mat and fibre mesh, which can improve the design flexibility of the fabric structure;
5) each reinforced insertion yarn layer can use different kinds of yarns, and the composition performance of the fabric can be extended [8].

Geometric model of multi-axial warp-knitted fabric

In order to do deep research on the geometric structure of multi-axial warp-knitted fabric with chopped strand mat, this paper employed NURBS curves and the principle of curved surface to develop 3D solid models to reflect the geometric structure of this kind of fabric. NURBS (Non-Uniform Rational B-Splines) can display the outline and shape via curves and curved surfaces in the interior space of 3D models. As NURBS have the excellent ability of controlling the curve degree of the surface, the shapes created by NURBS are more realistic and vivid compared with traditional grid modelling [9, 10].

In this paper, the researchers used the cubic polynomial of NURBS curves and the principle of curved surfaces to build a 3D solid model to reflect the geometric structure of MWK fabric more effectively. The NURBS curve can be used for representing the direction of the central axis of the yarn in the fabric, and a 3D model of the yarn can be built via the NURBS curved surface.

Basic assumptions

MWK fabric with chopped strand mat has three components: stitching yarns, reinforced insertion yarns and chopped strand mat. The MWK geometry can be characterised by three microstructure levels: the geometry of fibres which are packed in the yarn bundle (fibre level), the cross-section of yarn bundles in the fabric (yarn level), and the orientation and distribution of fibres in the 3D structure (fabric level) [6]. In order to make it convenient for later simulation and analytical calculation, before establishing a 3D geometric model of this fabric, the researchers defined some hypothetical conditions as follows:

1) The reinforced insertion yarns are usually glass fibre roving in which the monofilament's cross-section is circular. Since yarns are made up of lots of monofilaments, the thickness can reach 2400 tex × 2. Bound and squeezed in the process of knitting, the cross-section is flat, hence it can be assumed to be of a runway shape. In ***Figure 2.a***, where w_i refers to the width of insertion yarns, t_i refers to the thickness of insertion yarns, and $w_i/t_i > 1$.

2) Different stitching yarns are chosen depending on the properties which the final fabric demands. Stitching yarns can be formed by polyester or nylon with a small linear density when the fabric is simply subjected to an axial force; and in such a case, researchers always use 83.3 dtex 36f polyester. In addition, when the fabric needs layer strength, high-strength yarns are used as stitching yarns, for example, aramid fibre. It can be assumed that the cross-section of stitching yarns is circular since the cross-section is very small compared with insertion yarns' [11]. In ***Figure 2.b***, d_s refers to the diameter of stitching yarns.
3) The structure of the chopped strand mat is made up of a kind of discrete short fibre, which is composed of numerous chopped glass fibre yarns that have an approximate length (about 5 cm) and are laid at random. In the process of production, it will bear a certain force, hence the cross-section of single chopped glass fibre yarn

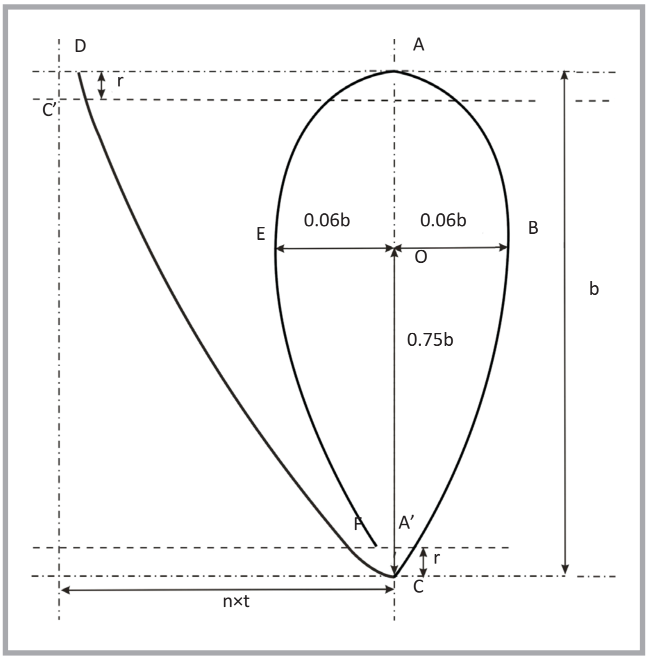

Figure 3. 3D loop model and its dimensions in the loop.

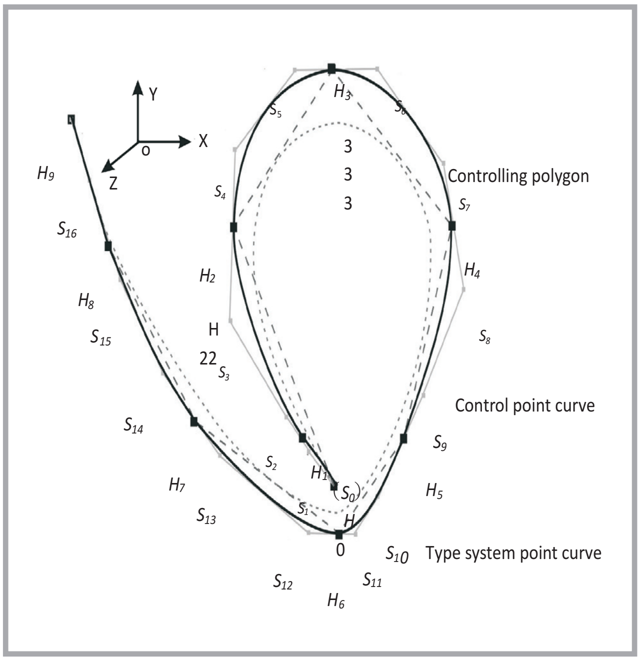

Figure 4. Loop model and control polygon of the curve.

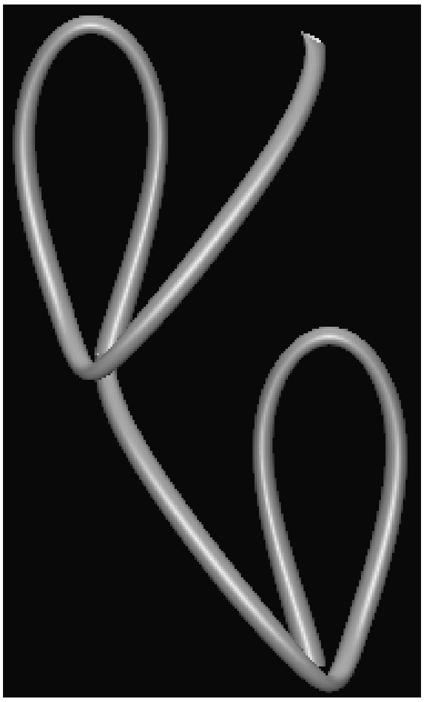

Figure 5. *Computer generated 3D image of closed loops.*

can also be assumed to be of a runway shape.

Three-dimensional solid model of stitching loop

The stitching loops of MWK fabrics are similar to those of common warp-knitted fabrics and can be divided into two components: one loop trunk and one underlap, with these two parts composing the whole. This paper did some research based on the 3D loop model proposed by reference [12]. Using the digital microscope system VHX-600, the researchers measured the structural parameters of stitching loops in MWK fabrics and analysed the experimental data. The model is shown in ***Figure 3*** and some postulated conditions are made as follows:

1) The vertical height b of the loop and height thereof are approximately equal;
2) The joint length of the loop is $r = 0.2b$;
3) The width of the loop is $w = |BE| = 0.12b$;
4) The distance from the center point of the widest part of the loop to the root thereof is $|OC| = 0.75b$;
5) The horizontal length of the underlap is $|AD| = n \times t - e$, in which n refers to the numbers of needle guages that the underlap strides across, t the distance between adjacent wales, and e is the fine tuning parameter that can be adjusted according to the loop shape.

In this paper, the researchers set up an *XYZ* coordinate system to define the bottom dot of the loop as the origin of coordinate *O*, the horizontal along the loop courses as the *X*-axis positive direction, the vertical along the loop wales as the *Y*-axis positive direction, and the fabric thickness direction, which was perpendicular to the *XOY* according to the right hand rule, as the *Z*-axis positive direction. The solid thick line in ***Figure 4*** forms the loop model, and 10 data points are used to define the loop. To make the loop connect more smoothly and naturally, more control points are put between adjacent data points in order to control the shape of the loop more exactly. In ***Figure 4***, $H_0 \sim H_9$ refer to the data points of NURBS curves, and $S_1 \sim S_{16}$ to the additional control points. The data and control points are coincident at the start and the end, thus the model of the stitching loop can be defined using 18 control points [13].

The researchers simplified the loop trunk into two lapping methods, 1-0 and 0-1, during drawing. When drawing the underlap, the researchers needed to identify the connecting situation of the underlap. The chain notations in the same course should be considered, and the relation between chain notations in the different courses should be recognised as well. ***Figure 5*** shows a 3D image of closed loops generated using computer software.

Three-dimensional solid model of reinforced insertion yarns

In MWK fabrics, the reinforced insertion yarns are inserted parallel-wise and straightly at certain angles. The cross-section was assumed to have a runway shape when the researchers were building the models and the distances between adjacent insertion yarns were the same. Here is an example of insertion warp yarns at the angle of 0°. ***Figure 6*** shows the model of reinforced insertion yarn, where *X* is the direction of courses, *Y* the direction of wales, and *Z* is the thickness direction of the fabric. Points *A* and *A'* refer to the centers of the upper and lower runway shaped cross-sections of the reinforced insertion yarns, and points *E* and *E'* are the centers of the semicircle in the runway shape. For a single reinforced insertion yarn, the shape of the yarn can be controlled by points *A*, *A'*, *E* and *F*. The length of the reinforced insertion yarn is based on $|AA'|$, the width on $|AE|$ and $|EF|$; the thickness depends on $|EF|$, and the relation between them is as follows:

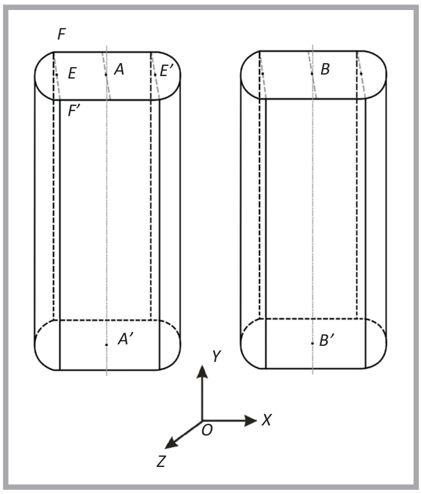

Figure 6. *Models of reinforced insertion yarns.*

$|AA'| = L$, the length of the reinforced insertion yarn, $(|EF| + |AE|) \times 2 = w_i$, the width of the reinforced insertion yarn, and $|EF| \times 2 = t_i$, the thickness of the reinforced insertion yarn.

BB' in this figure represents the central axis of the adjacent reinforced insertion yarn, which is parallel to the central axis *AA'*. The distance between the two adjacent insertion yarns is defined via the coordinates of points *A*, *A'*, *B* and *B'*, and the relation between them is as follows:

$|AB| - w_i = S$, the distance between the two adjacent insertion yarns.

Several groups of the models mentioned above compose one layer of reinforced insertion yarns. In order to express the insertion yarns at different angles and in different layers, the coordinates of each parameter on the *Z* axis simply changed, as well as the coordinates of each parameters in the *X-Y* plane according to the angle required. Taking the reinforced insertion yarn, which is at the angle of $+\theta$, as an example, it is assumed that the layer is below the 0° insertion yarn and then the model shown in ***Figure 7*** is obtained.

In ***Figure 7*** (see page 94), points A_1, A_1', M_1 and M'_1 are the separate projection points of the center line *AA'* of 0° insertion yarn and the center line *MM'* of $+\theta$ insertion yarn in the *XY* plane. Also point *O* is the projection point of the midpoint of the two center lines. According to the relationship shown in ***Figure 7***, we assume the coordinates of point *A* to be $(X_A, Y_A, 0)$, and the coordinates of other points can be calculated as follows:

$A'(X_A, Y_A - L, 0)$;
$A_1(X_A, Y_A, -3t_i/2)$;
$A'_1(X_A, Y_A - L, -3t_i/2)$;

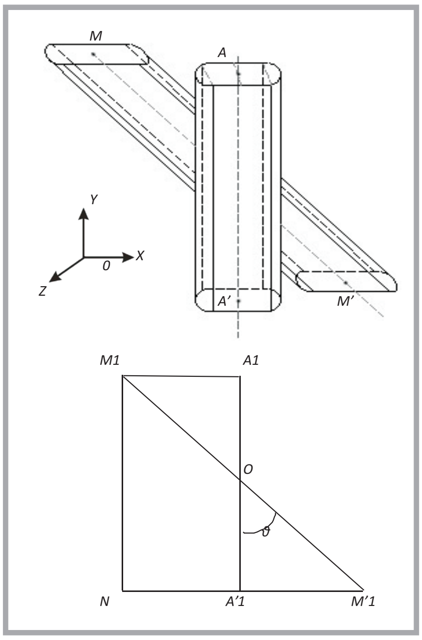

Figure 7. Model of insertion yarns in different layers.

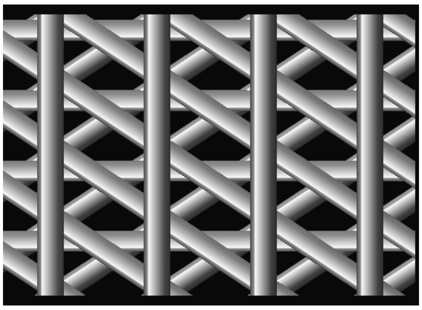

Figure 8. Computer generated 3D image of four-axial reinforced insertion yarns.

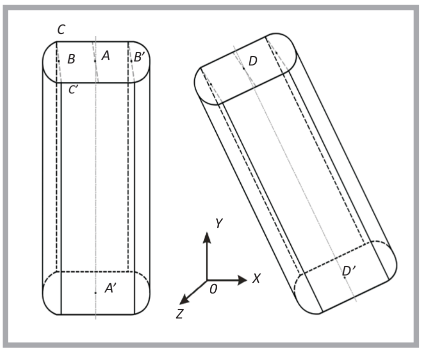

Figure 9. Model of chopped mat.

$M_1(X_A - (|AA'|\tan\theta)/2, Y_A, -3t_i/2)$;
$M'_1(X_A + (|AA'|\tan\theta)/2, Y_A-L, -3t_i/2)$;
$M(X_A - (|AA'|\tan\theta)/2, Y_A, -t_i)$;
$M'(X_A + (|AA'|\tan\theta)/2, Y_A-L, -t_i)$.

According to the analysis above, the coordinates of points A_1, A_1', M_1 and M'_1 are obtained. And then the dimensions and distribution of two different layers of insertion yarns at the angles of 0° and $+\theta$ can be known based on these coordinates, together with the width w_i and thickness t_i of the reinforced insertion yarn. Then the rest may be deduced by analogy and the placement of reinforced insertion yarns in the multiple layers recognized.

On the basis of the method of defining models of reinforced insertion yarns, four-axial reinforced insertion yarns can be simulated through a computer programming language. The 3-D simulation result is as shown in ***Figure 8.***

Three-dimensional solid model of chopped strand mat

The chopped strand mat in MWK fabric is composed of numerous chopped glass fibre yarns placed at random [14]. According to previous assumptions, the cross-section of single chopped glass fibre yarn can be assumed to have a runway shape. ***Figure 9*** shows the model of chopped glass fibre yarn.

It can be seen from ***Figure 9*** that the length of glass fibre yarns in the chopped strand mat is determined by the coordinates of point *A* and *A'*, and the method that defines the cross-sectional shape of this kind of yarn in the chopped strand mat is similar to that of reinforced insertion yarns. The cross-sectional shape of glass fibre yarns in the chopped strand mat can be determined by the coordinates of points *A*, *A'*, *B*, *B'*, *C* and *C'*. For the known structure of the chopped strand mat, if the structure of this chopped strand mat is to be simulated, some parameters should be set (such as the length of chopped glass fibre yarns, the yarn linear density, the area density of the chopped strand mat and so on) according to requirements. And the number of chopped glass fibre yarns in unit areas can be calculated as follows:

$$N = \frac{S \cdot M}{L \cdot \lambda} \times 10^3 \qquad (1)$$

where, N - the number of chopped glass fibre yarns, S – the area of the chopped strand mat in m^2, L – the average length of chopped glass fibre yarns in m, M - area density of chopped mat in $g \cdot m^{-2}$, λ - linear density of chopped glass fibre yarns in tex.

In addition, because the chopped glass fibre yarns are placed randomly in the chopped strand mat, their distribution can be approximated as a Poisson distribution. Thus when the dimensions and position of the first yarn in the chopped strand mat is determined, the distribution position of the next yarn as the coordinate of point *D* in ***Figure 9*** can be de-

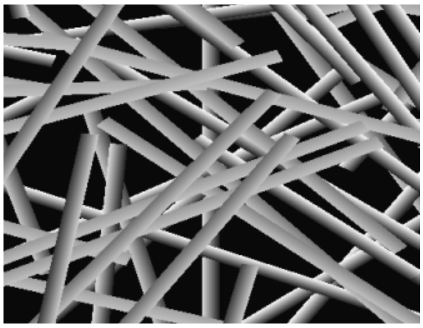

Figure 10. Computer generated 3D image of chopped mat.

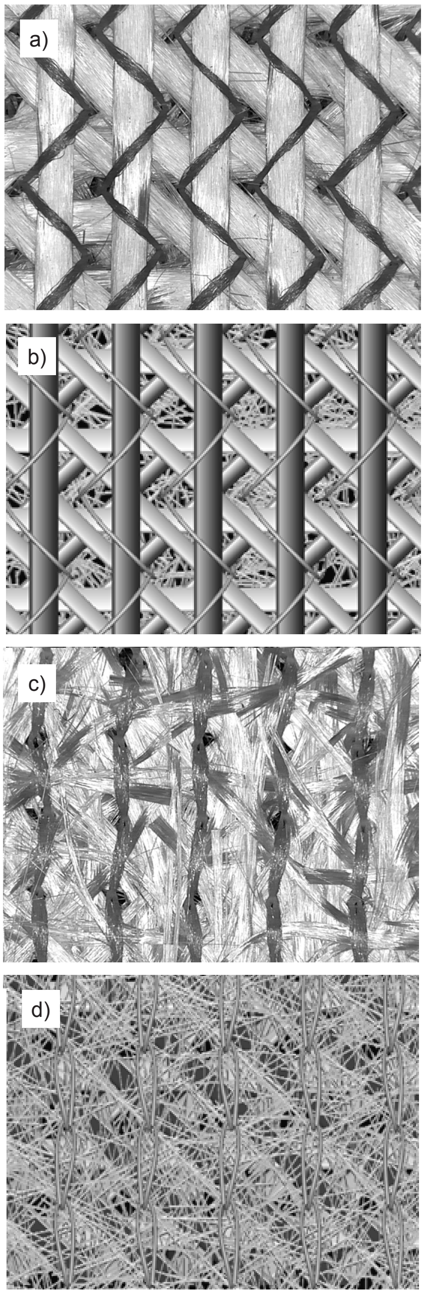

Figure 11. *Photomicrograph and 3D simulation image of quad-axial perform with chopped mat: a) Photomicrograph of technical back, b) 3D simulation image of technical back, c) Photomicrograph of technical face, d) 3D simulation image of technical face.*

rived from the Poisson distribution function. Meanwhile the angle distribution of single chopped glass fibre yarn in the chopped strand mat also conforms to the Poisson distribution.

$$P(X=k)=\frac{\lambda^k}{k!}e^{-\lambda}\ (k=0,1,2,\ldots) \quad (2)$$

in which $\lambda > 0$, and X obeys the Poisson distribution with parameter λ.

According to formula 2, it can be obtained that the orientation probability distribution function $\varphi(\theta)$ of chopped glass fibre yarns. In C++ standard library, there is a pseudo-random function generator rand(), which can simulate the Poisson distribution. Calling this function once each, we can obtain a different random number [15], for example, after the establishment of the coordinate of point *A*, can be used this random function to calculate the coordinate of point *D*. And then with the help of the coordinate of point *D*, the length of chopped glass fibre yarn and the angle obtained by the Poisson distribution function, the coordinate of point *D'* can be obtained. Thus the distribution of the second chopped glass fibre yarn in the chopped strand mat can be obtained. As the rest may be deduced by analogy, the distribution of *N* chopped glass fibre yarns in the chopped strand mat is revealed. ***Figure 10*** shows a 3D simulation image of the chopped strand mat.

Three-dimensional simulation of geometric model

Based on 3D solid models of MWK fabric that had been developed by the principle of NURBS, in this paper, the researchers wrote geometric models of the fabric into the computer program VC++. NET with the aid of the OpenGL image library, and developed a 3D simulation system of MWK fabric with the help of the NURBS interface brought about by OpenGL, together with the Microsoft Foundation class Library and Application Framework. The system can simulate a geometric model of fabric rapidly. Accordingly the intertexture of yarns in MWK fabric in a 3D space can be shown, which makes the pre-observation of the space structure of the fabric available before production. It has exceedingly practical significance for improving the design and production efficiency of MWK fabrics. ***Figure 11*** shows a simulation image of the technical back face and technical front face of four-axial warp-knitted fabric with chopped strand mat generated by the 3D simulation system, and also shows photomicrographs taken by the digital microscope system VHX-600.

Experimental verification of geometric model

By analysing the geometric parameters together with the process variables of the MWK fabric, a significant parameter (------ in ***Figure 12***) the fibre volume fraction formula of the fabric is obtained. It is an important parameter for the structure of fibre reinforced composite material, but also for the analysis, calculation and design of the micro-mechanical, which influences the final performance of composites directly [16]. Therefore this paper verified the correctness of the geometrical model through comparing the theoretical and experimental values of the fibre volume fraction.

This paper selected a unit cell to make the analysis of geometric models of the fabric easier. The dotted line in ***Figure 12*** draws a frame around the unit cell of four-axial warp-knitted fabric with a tricot texture generated by 3D computer simulation. According to the unit cell in ***Figure 12***, the unit cell model is built up based on four-axial warp-knitted fabric with chopped strand mat, as is shown in ***Figure 13*** (see page 96). In ***Figure 13***, the unit cell has five components: a 0° insertion yarn, a +θ insertion yarn, a 90° insertion yarn, a -θ insertion yarn and a layer of chopped strand mat. Research personnel usually define the 0° insertion yarn as the *X* axis, which is parallel to the machine direction, the 90° insertion yarn as the *Y* axis, which is vertical to the machine direction, and the thickness direction of the fabric as the *Z* axis, which is vertical to the *X-Y* plane [17]. However, in order to be consistent with the coordinate system of the previous NURBS model, according to the unit cell in ***Figure 13.a***, this paper defines the 0° insertion yarn as the *Y* axis and the 90° insertion yarn as the *X* axis, while the Z axis is the same as in the previous definition. The coordinate system can be shown in ***Figure 13.b***, and some dimensions of the unit cell are marked separetely in ***Figure 13.c*** and ***Figure 13.d***. After analysing the model, the dimension expressions of the unit cell, yarns and chopped strand mat

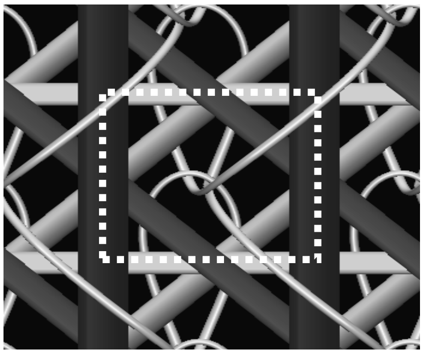

Figure 12. *Selection of the unit cell.*

can be derived. Thus the theoretical fibre volume fraction formula can be established.

As the stitching loop was formed by 18 control points based on the principle of NURBS, coordinates of the control points in the control polygon, shown in ***Figure 4*** are used, to calculate the length of the stitching yarn (***Equation 3***) where, L_S - length of stitching yarn in the unit cell/mm, $S_{i,j}$ - coordinates of control points in control polygon.

The dimensions of the unit cell can be obtained by the following formulas;

$$L_Y=\frac{2.54}{E_{\theta_{\max}}}\times 10 \quad (4)$$

where, L_Y - size of unit cell in *Y* axis/mm, $E_{\theta max}$ - density of reeds for the maximum angle of weft insertion in the unit cell (numbers of needles per 2.54 cm).

$$L_X=\frac{2.54}{E_Y}\times 10 \quad (5)$$

where, L_X - size of unit cell in *X* axis/mm, E_Y - density of reeds for warp insertion (machine gauge)/(numbers of needles per 2.54 cm).

$$L_Z=t_X+t_Y+t_v+t_{+\theta}+t_{-\theta}+3d_s \quad (6)$$

where L_Z - size of unit cell in *Z* axis/mm, t_X - thickness of 90° insertion yarn/mm, t_Y - thickness of 0° insertion yarn/mm, t_V - thickness of chopped strand mat/mm, $t_{+\theta}$ - thickness of +θ insertion yarn/mm, $t_{-\theta}$ - thickness of -θ insertion yarn/mm, d_S - diameter of stitching yarn/mm.

According to the configuration relationship between stitching yarns, the reinforced insertion yarns and chopped

$$L_S=\sum_{i=0}^{16}\sqrt{(S_{x,i+1}-S_{x,i})^2+(S_{y,i+1}-S_{y,i})^2+(S_{z,i+1}-S_{z,i})^2} \quad (3)$$

Equation 3.

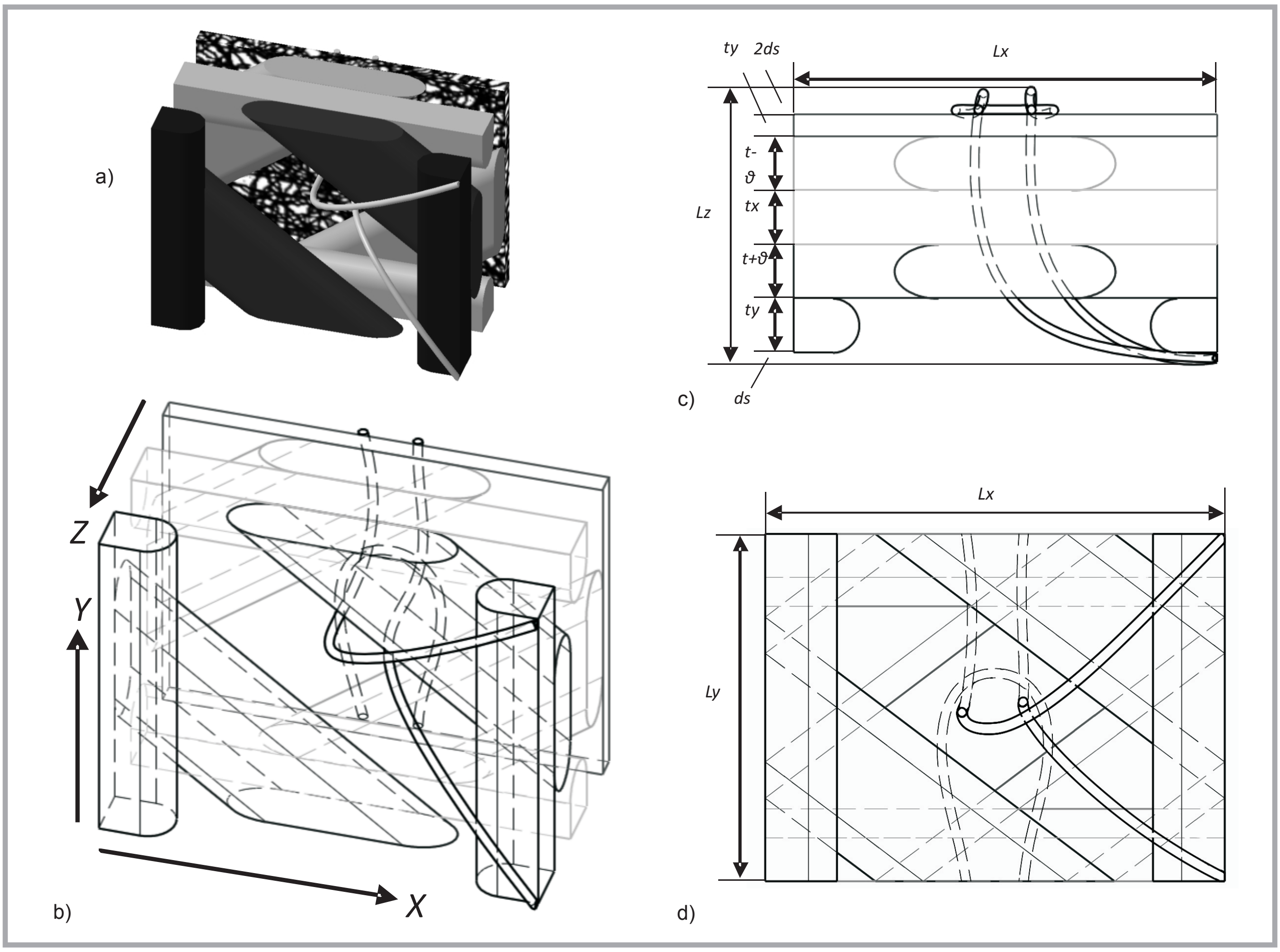

Figure 13. *Structure and size of the unit cell of qua-axial warp-knitted perform with chopped mat: a) three-dimensional image of unit cell, b) internal structure image of unit cell, c) top view of unit cell, d) main view of unit cell.*

strand mat in a unit cell of the fabric, the theoretical fibre volume fraction of four-axial warp-knitted fabric with a chopped mat can be derived (***Equation 7***) where, V_f - theoretical fibre volume fraction of fabric, V_s - volume of stitching yarn in mm^3, V_i - volume of reinforced insertion yarn in mm^3, V_V - volume of chopped strand mat in mm^3, λs - linear density of stitching yarn in tex, λ_i - linear density of reinforced insertion yarn in tex, L_i - length of reinforced insertion yarn in mm, λ_X - linear density of 90° insertion yarn in tex, λ_Y - linear density of 0° insertion yarn in tex, $\lambda_{+\theta}$ - linear density of $+\theta$ insertion yarn in tex, $\lambda_{-\theta}$ - linear density of $-\theta$ insertion yarn in tex, ρ_S - fibre density of stitching yarn in g·cm^{-3}, ρ_X - fibre density of 90° insertion yarn in g·cm^{-3}, ρ_Y - fibre density of 0° insertion yarn in g·cm^{-3}, $\rho_{+\theta}$ - fibre density of $+\theta$ insertion yarn in g·cm^{-3}, $\rho_{-\theta}$ - fibre density of $-\theta$ insertion yarn in g·cm^{-3}, ρ_V - glass fibre density of chopped strand mat in g·cm^{-3}, M_V - area density of chopped strand mat in g·m^{-2}.

After the creation of the theoretical fibre volume fraction formula, the researchers selected six kinds of MWK fabrics of different specifications to compose using VARTM. And the theoretical value of the fibre volume fraction was calculated efficiently by the calculation module in the 3D simulation system. Then after comparing the theoretical fibre volume fraction with the experimental one, the result indicated that the error between them is from 5 to 6%, which meant that the model was correct within a certain error range.

$$V_f = \frac{V_s + V_i + V_V}{V_c} = \frac{\dfrac{\lambda_s \cdot L_s}{\rho_s} + \dfrac{\lambda_i \cdot L_i}{\rho_i} + \dfrac{M_V \cdot L_X \cdot L_Y}{\rho_V}}{L_X \cdot L_Y \cdot L_Z} \times 10^{-3} =$$
$$= \frac{\dfrac{\lambda_s}{\rho_s} \cdot L_s + \dfrac{\lambda_X}{\rho_X} \cdot L_X + \dfrac{\lambda_Y}{\rho_Y} \cdot L_Y + \dfrac{\lambda_{+\theta}}{\rho_{+\theta}} \cdot \sqrt{L_X^2 + L_Y^2} + \dfrac{\lambda_{-\theta}}{\rho_{-\theta}} \cdot \sqrt{L_X^2 + L_Y^2} + \dfrac{M_V}{\rho_V} \cdot L_X \cdot L_Y}{L_X \cdot L_Y \cdot L_Z} \times 10^{-3} \quad (7)$$

Equation 7.

Conclusions

Through the research on the structure of modern MWK fabric with chopped strand mat, scientific and rational geometric models of the fabric were established by considering factors which influence it during production; and also a 3D simulation of the geometry was achieved. Furthermore the accuracy of this model was testified by experiments.

The following conclusions can be obtained from this paper:

1) Via research on the structural features of modern MWK fabrics with chopped strand mat, at the same time considering the relations between the geometric structure and the force borne by each yarn system in the knitting process, 3D solid models which can reflect geometric structures of modern MWK fabrics were developed based on the principle of NURBS curves and curved surfaces.
2) With the tools of VC++. NET and OpenGL graphics library, a 3D computer simulation system for MWK fabrics was developed. The system supports several functional modules and covered a wide range of MWK fabric structures, which can provide a powerful computer-aided platform for the design and production of MWK fabrics. With the help of this system, the design process can be simplified and the product development speed will be improved.
3) The theoretical fibre volume fraction formula of MWK fabric is obtained by analysis of the unit cell selected. And through comparing the theoretical fibre volume fraction with the experimental one, the result indicates that the fibre volume fraction is in good agreement with the theoretical and experimental values, which means that the model is correct within a certain error range. All of these provide useful and significant theoretical and experimental references for the prediction of the permeability and flow conductivity of MWK fabrics.

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