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COMPUTER GEOMETRIC MODELING APPROACH WITH FILAMENT ASSEMBLY MODEL FOR 2 × 1 AND 3 × 1 TWILL WOVEN FABRIC STRUCTURES

Puttipong Patumchat[1], Sudsakorn Inthidech[2], Yottha Srithep[2], Keartisak Sriprateep[2,*]

1 Department of Industrial Piping Technology, Faculty of Technical Education, Rajamangala University of Technology Isan Khonkaen Campus, Khonkaen, 40000, Thailand
2 Department of Manufacturing Engineering, Faculty of Engineering, Manufacturing and Materials Research Unit (MMR), Mahasarakham University, Mahasarakham, 44150, Thailand
*Corresponding author. E-mail: keartisaks@hotmail.com

Abstract:

A new computer geometric modeling approach for 2 × 1 and 3 × 1 twill woven fabric structures is proposed. The precise geometrical description is presented by taking the skewness property into account. In the 2 × 1 and 3 × 1 twill weaves, the twill fabrics are formed of asymmetric floatings in which the length of floating sections was not equal on both surfaces and therefore the equilibrium condition was different from symmetric floatings. The proposed algorithm has three main parts: the first part describes the two-dimensional model of yarn cross-section for twill woven fabric structure, the second part consists of a modeling method for a three-dimensional model in warp/weft yarn, and the third part contains the CAD model. Examples of this approach are demonstrated and compared with a single line of yarn path model and the filament assemble model that excludes the skewness property. The model simulated in this study can improve the visual simulation of the real twill woven fabric and also this geometric model necessary as an input to many computational models for the prediction of the properties of the fabrics.

Keywords:

2 × 1 and 3 × 1 twill weave, computer-aided design, geometric modeling, filament assembly model, skewness

1. Introduction

The first study on thread skewness of twill weave fabrics was carried out by Iyer et al. [1]. Under normal conditions, skewness is commonly found in twill weave structures when the average directions of the warp and weft yarns are not perpendicular to each other. Due to the force applied by other yarns when the yarn skews during long floating regions, it skews in the opposite direction during the intersecting motion and turns back to its former position. There is a space between the two yarns over which a thread floats and the free space makes it possible for the floating yarn at the interlacing point to push away the crossing yarn. The degree of movement of the free space is related to the character of yarn, the weaving tensions, and the fabric structure. The 2 × 1 and 3 × 1 twill weaves are twill fabrics formed of asymmetric floatings. Therefore, the yarn path of these twills could not be modeled like 2/2 twill weaves. But in twill weaves (2 × 1 and 3 × 1 twill), the length of floating sections is not equal on both surfaces and therefore the equilibrium condition is different from symmetric floatings [2].

Turan and Okur [2] used the B-spline method to obtain visual simulations of 2 × 1 and 3 × 1 twill weave woven fabrics based on single-line yarn path. The inherent skewness of twill fabric in the floating region was taken into consideration for modeling. Depending on structural parameters and the inherent skewness property of experimental results, reliable twill weave models are achieved which would be helpful in computer applications. Turan and Baser [3] also carried out visual simulations of 2 × 2 twill weave woven fabrics using the B-spline method to convert the yarn path to a smooth curve. In constructing the model, the yarn paths were divided into small linear segments and the direction angles of yarn central axes were determined. In one study, Alamdar-Yazdi [4] produced nine woven fabrics in different weaves and investigated these fabrics' new shapes after relaxation; deformations of fabrics were different due to the weave structure. This experimental study showed that among nine different weaves 3 × 3 twill weave had the highest skewness. In twill fabrics, there is a space between the two yarns over which a thread floats. This free space makes it possible for the floating yarn at the interlacing point to push away the crossing yarn. The degree of movement is related to the character of the yarn, the weaving conditions (especially the weaving tensions), and the fabric structure. Also, in another study, Alamdar-Yazdi [5] examined new shapes of the twill and herringbone fabrics after 48 h of relaxation. He observed that the shape of all fabrics became like a parallelogram but with different sizes. This shows that fabric deformation during relaxation depends upon the fabric structure and the skewness of fabric depends upon the location of free spaces, float length, and number of free spaces. Konopasek and Shanahan [6] described a mechanical model of the 2/2-twill weave based on a representation of constitutive yarns by means of three-dimensional (3D) elastica. The model is formulated in terms of the UMIST Bending Curve Program package and illustrated by a few computed examples. Also, a theoretical analysis for predicting the tensile modulus of 2/2 twill woven fabrics in their initial state of uniaxial load-extension behavior presented by Avanaki et al. [7]. The proposed theory was compared and validated by applying into some experimental data.

CAD modeling of 2 × 1 and 3 × 1 twill weaves with precise geometrical description of twill woven structures provides valuable information to both manufacturers and designers. The geometric model is a true visual simulation of real woven fabric and necessary as an input to many computational models for the prediction of the properties and in-use behavior of the fabrics such as prediction of the air permeability or heat transfer or the mechanical properties. For example, Sriprateep and Bohez [8] successfully used a CAD/CAE model with a filament model to predict the stress–strain curves of yarn structures and also Sriprateep [9] used a CAD/CAE model to predict the stress–strain curves of a wide range of multifilament twisted man-made filament yarns. In their previous works, they regarded geometrical modeling of yarn structure as based on a single line yarn path [2,3,10–14] and developed models to display the visual characteristics of real yarns, ply yarns, woven fabrics, and knitted fabrics. These presentations were limited to virtual representation and prediction of the properties. Therefore, Sriprateep and Bohez [15–17] have developed a CAD model of fiber and yarn as an assembly of many filaments by twisting of single yarn, two ply yarn, and woven fabric structures.

The main objective of this study is to develop a model of yarn structure for 2 × 1 and 3 × 1 twill woven structures as an assembly of many fibers by twisting, using computer-aided design (CAD). Their inherent skewness has been included to the model and can be used in precise geometrical description. The 3D geometrical model considered that the yarn paths were divided into small linear segments and assumed circular geometry for yarn cross-section. The direction angles of yarn central axes were determined using the B-spline method to convert the yarn path to a smooth curve. Examples of the method are illustrated.

2. New proposed geometric model

The proposed new algorithm has three main parts. The first part describes the two-dimensional (2D) model of yarn cross-section for twill woven fabric structure based on their inherent skewness. The second part consists of a modeling method for the 3D model in warp/weft yarn and the third part contains the CAD model. The major steps for constructing the model are shown in Figure 1. The geometric parameters input to the model are the same as in the study of Patumchat and Sriprateep [16] ($d_{1,i}$, $d_{2,i}$, $p_{1,i}$, $p_{2,i}$, h_1, h_2, θ_1, θ_2, α_1, α_2, d_f, N_f, N_z) but additional parameters consist of warp/weft yarn spacing of the sinking ($p_{1pi} + c$) or floating ($p_{2pi} + c$), warp/weft floating length (l_{f1}, l_{f2}), warp/weft intersection length (l_{s1}, l_{s2}), warp/weft skewness angle of the floating length (δ_1, δ_2), warp/weft return angle of the intersection region (β_1, β_2), and the return of yarn movement (M_{f1}, M_{f2}). In this work, it is assumed that warp and weft are globally orthogonal.

2.1. 2D model of yarn path skewness and yarn cross-section

2.1.1. Geometrical model of the yarn path skewness segments

The forces affecting the yarns and the formation of skewness for 2 × 1 twill woven fabrics are shown in Figure 2(a–d), which also shows the 2D geometrical model of linear yarn path skewness segments that illustrates the projection of floating and intersecting yarn segments. Figure 3 illustrates the coordinate system of filaments in yarn cross-section for 2 × 1 and 3 × 1 twill weave fabric structures and the linear yarn path skewness of the unit weave length (pr), respectively. In the case of the 2 × 1 and 3 × 1 twill weaves, the unit weave length was defined in equations (1) and (2) as related to the projection length of floating (l_f) and the intersection region (l_s). The warp yarn float makes an angle with the y axis, which is the skewness angle shown by δ; the intersection line makes an angle β with the y axis and the warp and weft settings of the fabric (S_1, S_2), respectively. In the equations, subscripts 1 and 2 refer to parameters in the warp and weft directions, respectively, as shown below.

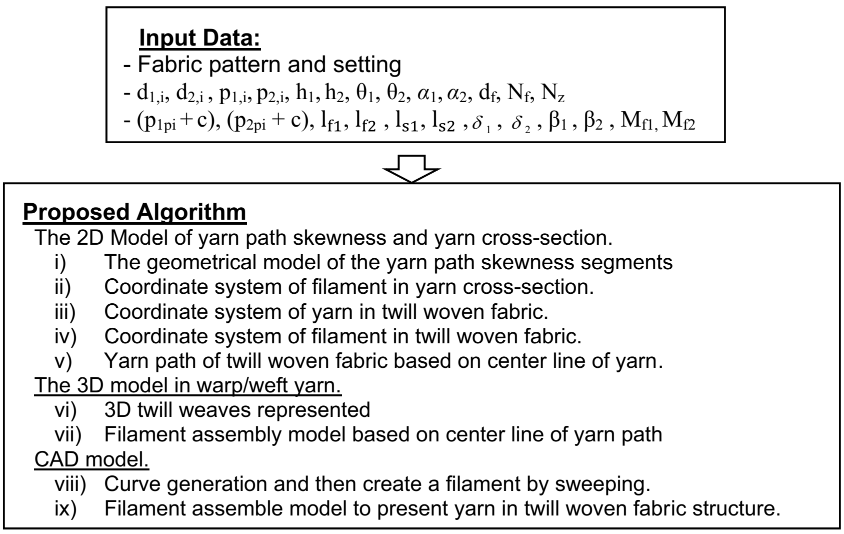


Figure 1. Major steps of the computer modeling approach for constructing 3D 2 × 1 and 3 × 1 twill woven fabrics.

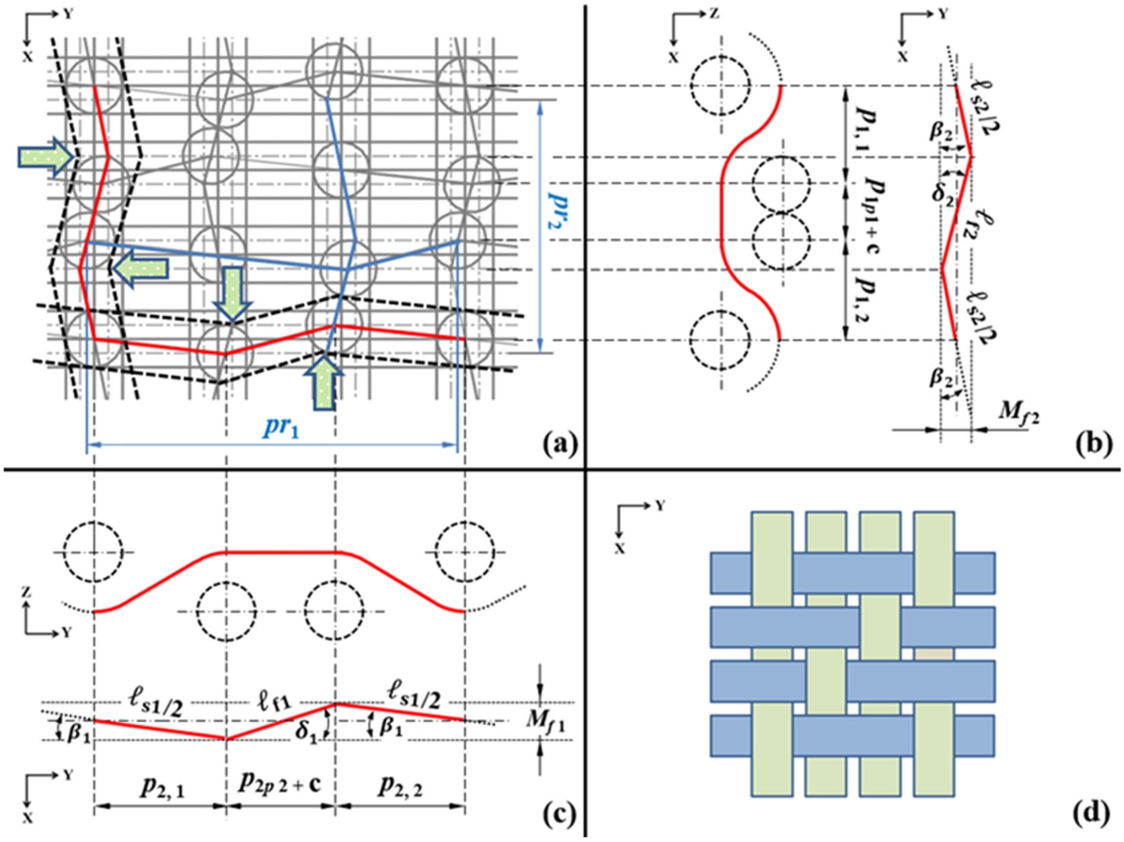


Figure 2. The forces affecting yarns and the formation of skewness for 2 × 1 twill woven fabrics: (a) top view with forces affecting yarns, (b and c) the projection linear yarn path, and (d) top view without forces affecting yarns.

For 2 × 1 twill weaves

$$\mathrm{pr}_1 = \frac{3}{S_2} = l_{f1}\cos\delta_1 + l_{s1}\cos\beta_1, \tag{1}$$

and for 3 × 1 twill weaves

$$\mathrm{pr}_1 = \frac{4}{S_2} = l_{f1}\cos\delta_1 + l_{s1}\cos\beta_1. \tag{2}$$

In the 2 × 1 and 3 × 1 twill weaves, we used the values of free space (c) between the two yarns over the floating region. The free space makes it possible for the floating yarn to push away the crossing yarn at the interlacing point [4]. In the floating region, the floating length of warp yarn can be estimated as follows:

$$l_{f2} = \frac{p_{1p1} + c}{\cos\delta_2}. \tag{3}$$

The intersecting length of warp yarn in the intersecting region can be estimated as follows:

$$l_{s2} = \frac{p_{1,1}}{\cos\beta_2}. \tag{4}$$

The skewness angle (δ, β), the floating length (l_f), and the intersecting length (l_s) were determined in equations (1)–(4). Therefore, the projection of the linear lines of the return yarn movement region (M_{fi}) of warp or weft yarn in the floating and intersection region on the XY plane is obtained by:

$$M_{f1} = M_{f2} = d_i/2. \tag{5}$$

The coordinate system of filaments in twill woven fabrics and the projection of linear yarn path of the floating and intersecting region for 2 × 1 and 3 × 1 twill weaves are shown in Figure 3(a–d), respectively. The origin point of the 2D model (X = 0, Z = 0) of yarn in 2 × 1 twill woven fabric in the XZ axis is shown in Figure 3(a). Some of the twill woven fabric parameters are also shown in the figure. In this study, a geometrical model considering their inherent skewness has been proposed, which can be used in precise geometrical description of twill woven structures. The characteristic property of twill weaves is that the warp/weft floatings and intersectings are not perpendicular, but form an angle. Figure 3(b) shows the projection of linear yarn path of the floating and intersecting region on the XY plane for 2 × 1 twill weave. Figure 3(c) illustrates the origin point of the 2D model (Y = 0, Z = 0) of yarn in 3 × 1 twill woven fabric in the YZ axis and also the projection of linear yarn path of the floating and intersecting region on the XY plane for 3 × 1 twill weave is illustrated in Figure 3(d).

2.1.2. Coordinate system of filament in yarn cross-section

The concept of virtual location is used to simulate the fiber distributions in yarn cross-section of 2 × 1 and 3 × 1 twill woven

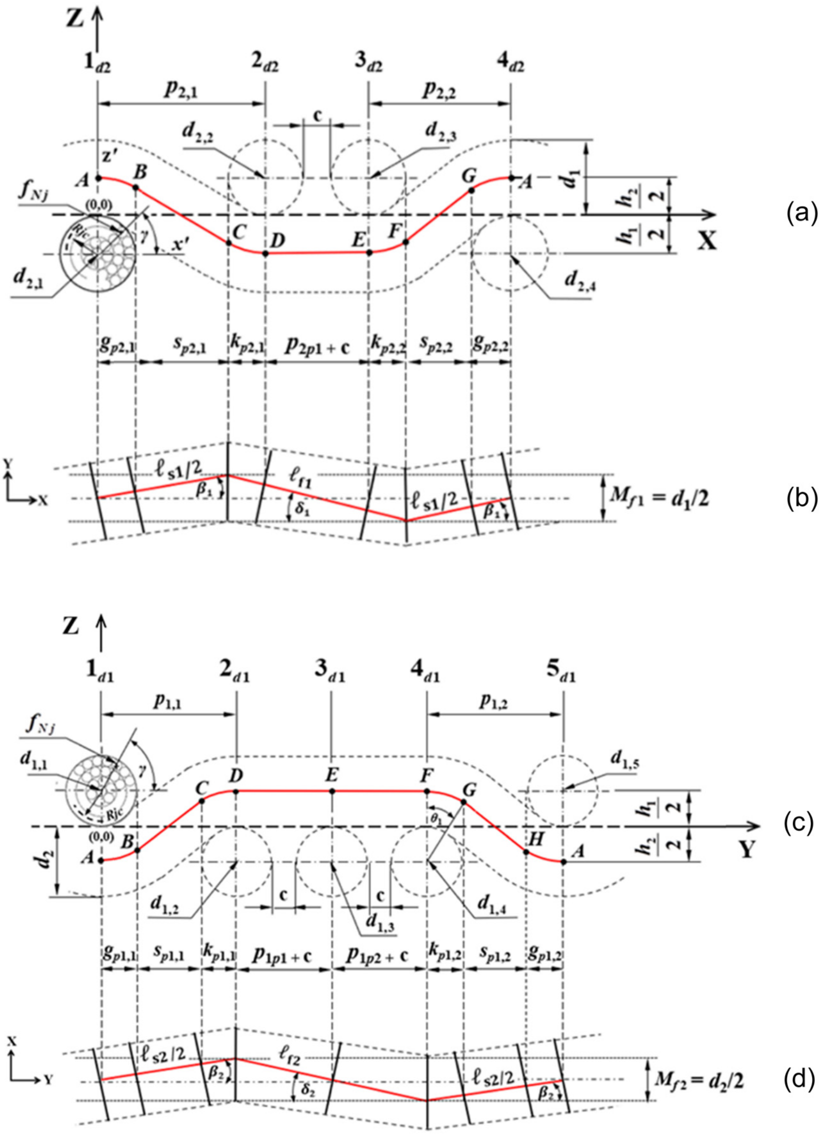


Figure 3. Coordinate system of filaments in twill woven fabrics and the projection of linear yarn path of floating and intersecting regions: (a and b) 2 × 1 and (c and d) 3 × 1 twill weave.

fabrics. The Cartesian coordinates from polar coordinates of the center of yarn to coordinate system $x'z'$ are as follows:

$$f_{Nj}^{x'} = R_{jc}\cos\gamma, \quad (6)$$

$$f_{Nj}^{z'} = R_{jc}\sin\gamma. \quad (7)$$

The coordinate system of yarn cross-section in $y'z'$ is as follows:

$$f_{Nj}^{x'} = R_{jc}\cos\gamma, \quad (8)$$

$$f_{Nj}^{z'} = R_{jc}\sin\gamma. \quad (9)$$

2.1.3. Coordinate system of yarn in twill woven fabric

In the 2 × 1 and 3 × 1 twill weave fabric structures, the position of the center fabric structure is characterized by Cartesian coordinates (X, Z) and (Y, Z) of the center of twill woven fabric structure (X = 0, Z = 0) and (Y = 0, Z = 0) that are shown in Figure 3(a) and (c), respectively. In 2D twill weave, the number of warp/weft yarns were defined as i_{d1} (1, 2,…, N_1) or i_{d2} (1, 2,…, N_2). The coordinates for warp yarn of the center of yarn at i_{d1} in the Y axis for 2 × 1 and 3 × 1 for one unit cell twill weave fabric are defined as follows:

For 2 × 1 twill weave fabric, the equation is as follows:

$$d_i^{Y} = (p_{1,1})2_{d1} + (p_{1P1} + c)3_{d1} + (p_{1,2})4_{d1}. \quad (10)$$

For 3 × 1 twill weave fabric, the equation is as follows:

$$d_i^{Y} = (p_{1,1})2_{d1} + (p_{1P1} + c)3_{d1} + (p_{1P2} + c)4_{d1} + (p_{1,2})5_{d1}. \quad (11)$$

The coordinates of weft yarn in the X axis and the coordinate of center of yarn at i_{d2} are defined in the same way as in equations (10) and (11). The position of the center fabrics structure is characterized by Cartesian coordinates (X, Z) of the center of the one unit cell twill woven fabric structure (X = 0, Z = 0).

For 2 × 1 twill weave fabric, the equation is as follows:

$$d_i^X = (p_{2,1})2_{d2} + (p_{2P1} + c)3_{d2} + (p_{2,2})4_{d2}. \tag{12}$$

For 3 × 1 twill weave fabric, the equation is as follows:

$$d_i^X = (p_{2,1})2_{d2} + (p_{2P1} + c)3_{d2} + (p_{2P2} + c)4_{d2} + (p_{2,2})5_{d2}. \tag{13}$$

The 2 × 1 twill weave was formed of asymmetric floatings indicated in Figure 3(a and b), which shows the center line of the yarn path at the point $A, B, C,\ldots, G, A$ along the yarn length on the XZ plane. The main dimensionless parameters are $p_{2,1}$ $(g_{p2,1}, s_{p2,1}, k_{p2,1})$, $p_{2,2} = (k_{p2,2}, s_{p2,2}, g_{p2,2})$ and $p_{2p1} + c$ is the spacing of center line of yarn at the point on the XZ plane. For the 3 × 1 twill weave, the unit length of yarn path based on center line of yarn point $A, B,\ldots, H, A$ on the YZ plane is shown in Figure 3(c and d). The main dimensionless parameters are $p_{1,1}$ $(g_{p1,1}, s_{p1,1}, k_{p1,1})$, $p_{1,2} = (k_{p1,2}, s_{p1,2}, g_{p1,2})$, $p_{1p1} + c$ and $p_{1p2} + c$ is the spacing of the center line of the yarn at the point on the YZ plane. For 2 × 1 and 3 × 1 twill weaves, the center line of the yarn path made an angle by skewing in the floating region (δ_i), and then it made an angle in the intersecting region (β_i) of the linear part of yarn segment. θ_i is the crimp angle of the yarn.

The crimp value in the Z axis is accepted as the fabric thickness direction that is derived from the linear segmented model of yarn path of 2 × 1 and 3 × 1 twill structure. The coordinate system of (X, Z) or (Y, Z) of the twill woven fabric structure can be separated into two parts: the first part was defined as positive (+) $h_i/2$ and the second part was defined as negative (−) $h_i/2$. In the Z axis, the coordinate of $h_i/2$ is defined as:

$$d_i^Z = \pm h_i/2 \begin{cases} \dfrac{h_2}{2}, & \text{where the coordinate of yarn in the upper quadrant regions,} \\ -\dfrac{h_2}{2}, & \text{where the coordinate of yarn in the lower quadrant regions.} \end{cases} \tag{14}$$

2.1.4. Coordinate system of filament in twill woven fabric

Equations (6)–(9) are defined as the coordinate system (x', z') or (y', z') of filament in yarn cross section and also equations (10)–(14) are calculated for the coordinate system (X, Z) or (Y, Z) of yarn in twill woven fabric structures. The coordinates of the Nth filament of jth layers on the X axis ($f_{Nj}^X d_i$), on the Y axis ($f_{Nj}^Y d_i$), and on the Z axis ($f_{Nj}^Z d_i$) can be defined. The positions of the filaments in yarn cross section of i_{d2} in the X axis are as follows:

$$f_{Nj}^X d_i = d_i^X + R_{jc}\cos\gamma \quad \text{or} = d_i^X + f_{Nj}^{x'}. \tag{15}$$

In yarn cross section of i_{d1} in the Y axis, the positions of the filaments are defined as:

$$f_{Nj}^Y d_i = d_i^Y + R_{jc}\cos\gamma \quad \text{or} = d_i^Y + f_{Nj}^{y'}. \tag{16}$$

Also, the positions of filaments in twill wave fabric of i_{d1} or i_{d2} in the Z axis are as follows:

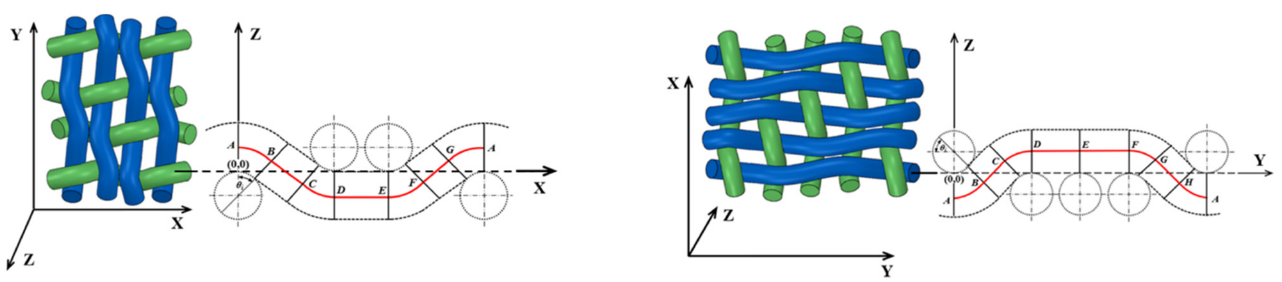
$$f_{Nj}^Z d_i = \pm h_i/2 + R_{jc}\sin\gamma \quad \text{or} = d_i^Z + f_{Nj}^{z'}. \tag{17}$$

2.2. 3D model in warp/weft yarn

2.2.1. 3D twill weaves represented

The fabric pattern and setting were designed. The automatic generation of 2D and 3D weaves represented by 2D binary matrices to a general vector matrix was developed by Jiang and Chen [14] and was extended by Patumchat and Sriprateep [16]. The structure of the initial vector matrix H_0 of the deflection of the yarns can be obtained. In this work, we used the element vectors for 2 × 1 and 3 × 1 twill weaves that are shown in Figure 3 that connected points ($A, B, C,\ldots, A$) of the center line of the yarn path along the yarn length. The structure of one unit cell for 2 × 1 twill weave, the number of connected points of the piecewise for the arc abscissa models in warp and weft directions is 8 points, and also one unit cell for 3 × 1 twill weave in warp and weft directions is 9 points, respectively. The fabric pattern and setting of twill weave were designed, so the structure of the initial vector matrix H_0 in the floating region in warp or weft of 2 × 1 twill weave ($A_{1\text{ or }2}, D_{1\text{ or }2}, E_{1\text{ or }2}, A_{1\text{ or }2}$) and 3 × 1 twill weave ($A_{1\text{ or }2}, D_{1\text{ or }2}, E_{1\text{ or }2}, F_{1\text{ or }2}, A_{1\text{ or }2}$) of the yarns can be obtained as follows:

$$H_{0(2\times1)} = \begin{bmatrix} \overrightarrow{T}_{A_1,A_2} & \overrightarrow{T}_{D_1,D_2} & \overrightarrow{T}_{E_1,E_2} & \overrightarrow{T}_{A_1,A_2} \\ \overrightarrow{T}_{E_1,E_2} & \overrightarrow{T}_{A_1,A_2} & \overrightarrow{T}_{D_1,D_2} & \overrightarrow{T}_{E_1,E_2} \\ \overrightarrow{T}_{D_1,D_2} & \overrightarrow{T}_{E_1,E_2} & \overrightarrow{T}_{A_1,A_2} & \overrightarrow{T}_{D_1,D_2} \\ \overrightarrow{T}_{A_1,A_2} & \overrightarrow{T}_{D_1,D_2} & \overrightarrow{T}_{E_1,E_2} & \overrightarrow{T}_{A_1,A_2} \end{bmatrix}, \tag{18}$$



(a) (b)

Figure 4. Projection on planes XZ and YZ for (a) 2 × 1 and (b) 3 × 1 twill weaves.

$$H_{0(3\times1)} = \begin{bmatrix} \overrightarrow{T}_{A_1,A_2} & \overrightarrow{T}_{D_1,D_2} & \overrightarrow{T}_{E_1,E_2} & \overrightarrow{T}_{F_1,F_2} & \overrightarrow{T}_{A_1,A_2} \\ \overrightarrow{T}_{F_1,F_2} & \overrightarrow{T}_{A_1,A_2} & \overrightarrow{T}_{D_1,D_2} & \overrightarrow{T}_{E_1,E_2} & \overrightarrow{T}_{F_1,F_2} \\ \overrightarrow{T}_{E_1,E_2} & \overrightarrow{T}_{F_1,F_2} & \overrightarrow{T}_{A_1,A_2} & \overrightarrow{T}_{D_1,D_2} & \overrightarrow{T}_{E_1,E_2} \\ \overrightarrow{T}_{D_1,D_2} & \overrightarrow{T}_{E_1,E_2} & \overrightarrow{T}_{F_1,F_2} & \overrightarrow{T}_{A_1,A_2} & \overrightarrow{T}_{D_1,D_2} \\ \overrightarrow{T}_{A_1,A_2} & \overrightarrow{T}_{D_1,D_2} & \overrightarrow{T}_{E_1,E_2} & \overrightarrow{T}_{F_1,F_2} & \overrightarrow{T}_{A_1,A_2} \end{bmatrix}. \quad (19)$$

$\overrightarrow{T}_{A_1,A_2}$ is the vector of the distance between the yarn centerline and center plane of the twill fabrics at the original point ($X = 0$, $Y = 0$, $Z = 0$) relative to the connected points of the linear segment of yarn path in warp ($A1$) and weft ($A2$) directions, respectively (Figure 4).

2.2.2. Filament assembly based on center line of yarn path

The center line of yarn in twill woven fabric structure was explained in the previous section. The circular geometry for yarn cross-section is perpendicular to the centerline yarn path along the yarn length. The data points of coordinates x_i, y_i, z_i of the crimp weave in each cross section can be obtain in the vector matric H_0(2 x 1) and H_0(3 x 1). The projected radius of the crimp weave at the first layer ($R_{jc} = 0$) and the filaments in outer layers are arranged with open packing form using the virtual location concept. Each cross-section is rotated along the length of yarn path by a pre-determined amount in respect of the previous one allowing for the yarn twist. In the 2 × 1 twill weave, the projection of outer layers (x', z') of filament in the yarn cross section is defined in equations (6) and (7) and the coordinate system (X, Y) of yarn in twill woven fabrics is calculated by equations (10), (12), and (14). Therefore, the positions of filaments in woven fabrics in the X and Y axes are defined by equations (15) and (16). The positions of filaments in the Z axis are defined by equation (17). For the coordinate system (y', z') of filament in yarn cross-section and coordinate system (Y, Z) of yarn in twill woven fabrics is calculated in the same way, but using different axes. In the 3 × 1 twill weave, the projection of outer layers (x', z') or (y', z') of filament in yarn cross section, the coordinate system (X, Y) of yarn in twill woven fabrics and the positions of filaments in woven fabrics are calculated in the same way. In 2 × 1 and 3 × 1 twill weaves, the center line of the yarn path makes an angle by skewing in the floating region (δ_i), and then it makes an angle in the intersecting region (β_i) of the linear part. The coordinates of filaments in each cross section on the normal plane of centerline of yarn, therefore, in the warp direction along the yarn length (x_i) will be at (y_i, z_i) and the filament in the weft direction along the yarn length (y_i) will be at (x_i, z_i). The projection of the filaments with their inherent skewness in outer layers of warp/weft directions can be calculated by:

$$\text{For warp: } \begin{cases} x' = x_i - R_{jc}\sin(\gamma)\sin\theta_i \\ y' = y_i + [R_{jc}\cos(\gamma+\psi)\cos\theta_i]/\cos(\delta_i)\cos(\beta_i) \\ z' = z_i + R_{jc}\sin(\gamma+\psi)\cos\theta_i, \end{cases} \quad (20)$$

$$\text{For weft: } \begin{cases} x' = x_i + [R_{jc}\cos(\gamma+\psi)\cos\theta_i]/\cos(\delta_i)\cos(\beta_i) \\ y' = y_i - R_{jc}\sin(\gamma)\sin\theta_i \\ z' = z_i + R_{jc}\sin(\gamma+\psi)\cos\theta_i. \end{cases} \quad (21)$$

In equations (20) and (21), if the angle is formed by skewing in the intersection region (β_i), then the angle in the floating region (δ_i) is zero degrees. Also if an angle is formed by skewing in the floating region (δ_i), then the angle in the intersecting region (β_i) is zero degrees.

2.3. CAD model of twill woven fabric structure

The projection of the centerline yarn path and the filaments in outer layers of warp or weft directions (x', y', z') can be calculated by equations (20) and (21). In 2 × 1 and 3 × 1 twill wave fabrics and considering the inherent skewness, the filament curve in each interval between two successive cross-sections can be approximated by a cubic NURBS curve in which the main components are the 2D or 3D control points or control vertices. The weights of these points and a knot vector limit the effect of the control vertices onto a given segment of the curve. Given data points $\overrightarrow{T}_{a,b}(t)$ for the centerline of yarn path and $\{d_i\}$ of coordinate x', y', z' of the filaments in each cross-section and associating parameters $\{\overrightarrow{r}(t)\}$, $i = 0, 1, \ldots, m$. The approximation curve $\overrightarrow{r}(t)$ in the least squares sense is defined as follows [18]:

$$\text{Minimize } \sum_{i=0}^{m} \|di - \overrightarrow{r}(t)\|^2. \quad (22)$$

The user specifies the points and the curve to pass this point as closely as possible in each interval between two successive cross-sections. The sweeping of a closed curve along a centerline path is created and a solid model of yarn structures can be represented.

3. Results and discussion

Due to their inherent skewness, we included the skewness property of 2 × 1 and 3 × 1 twill weaves and structure parameters into consideration while modeling the 3D geometry with the filament assembly model used for modeling the twill fabric structures. Turan and Okur [2] also used the B-spline method for modeling 2 × 1 and 3 × 1 twill fabric structures. They used experimental fabrics with structural properties of cotton fabrics of 2 × 1 and 3 × 1 twill weaves in order to obtain the 3D geometry of fabrics. Some structural properties of fabrics such as setting, yarn count, fabric thickness, and skewness angle in the direction of weft and warp yarns for twill weaves were used as input values to the model. The statistical results showed that the structural parameters of the real twill fabrics could be predicted by using the outputs of this geometrical model. They illustrated the three-dimensional simulations of 2 × 1 and 3 × 1 twill fabrics using a single line of yarn path with ellipse yarn cross-section and actual fabric. The model of twill weaves is defined by taking the skewness property into account. The comparison between the model and actual image found that the simulations had greater open area due to the model assuming the yarn cross-section to be solid and constant of yarn path. Also, in real fabrics, the shape of yarn changes according to yarn geometry. Figure 5(a–c) shows the comparison of 2 × 1 twill weave between single line of yarn path model [14], single line of yarn path model incudes the skewness property [2], and filament assemble model [16], respectively.

In this study, the SolidWorks 2018 software package was used to model the filament assembly that includes the skewness property. A CAD modeling approach is provided in Figure 1. Figures 6 and 7 report 3D computer simulations of 2 × 1 and 3 × 1 twill weaves fabric with isometric view, top view, and cross-section at center line of yarn path for warp/weft yarn.

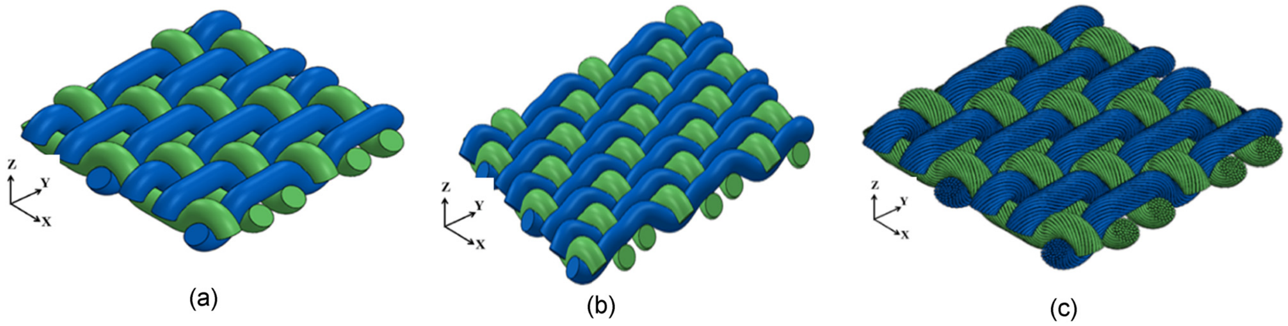


Figure 5. Comparison of 2 × 1 twill weave between (a) single line of yarn path model [14], (b) single line of yarn path model includes the skewness property [2], and (c) filament assemble model [16].

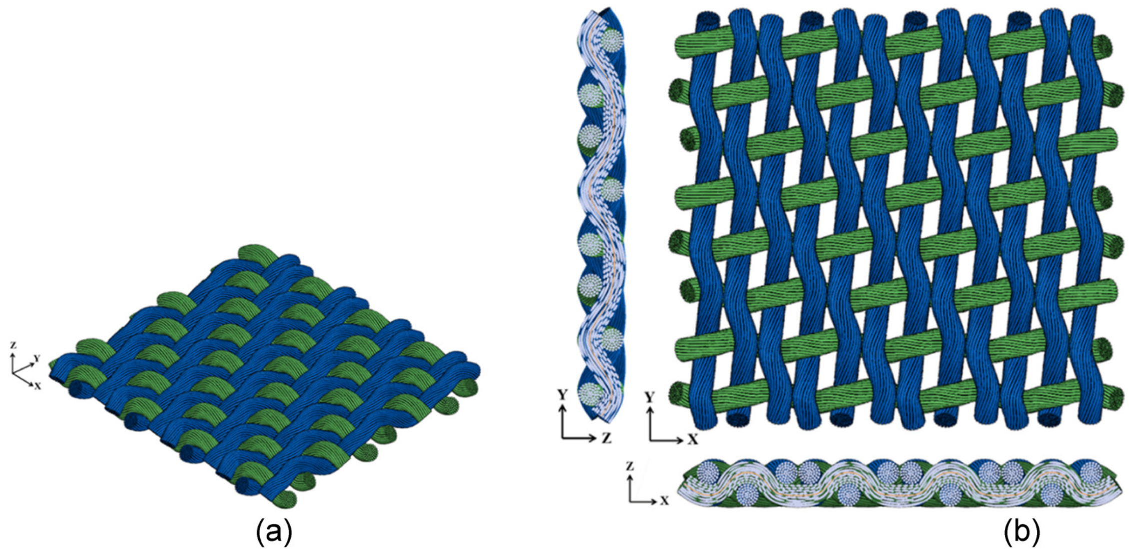


Figure 6. CAD of 2 × 1 twill weave fabric: (a) isometric view and (b) top view and cross-section at center line of yarn path for warp/weft yarn.

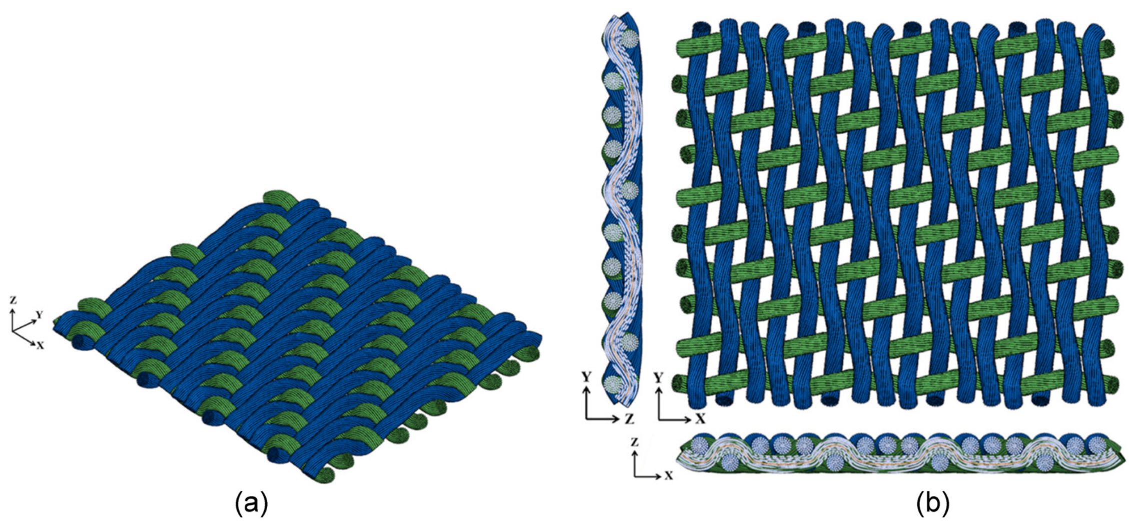


Figure 7. CAD of 3 × 1 twill weave fabric: (a) isometric view and (b) top view and cross-section at center line of yarn path for warp/weft yarn.

The experimental data in this study were used from the experimental results of Turan and Okur [2], especially the skewness property of twill weaves used in the models. Therefore, this model compared with the single line of yarn path model includes the skewness property [2]. The input parameter of each twill woven fabric structure for the circular yarn diameter in the warp/weft was 0.108 mm and filament diameter was 0.012 mm. The haft crimp wave height was 0.108 mm. The number of layers in the yarn cross section was 5 and the number of filaments was 56. The twist angle (degree) in warp/weft yarn structure was 25.80 and 18.60, respectively. Additional parameters included the skewness property consisting of the warp/weft skewness angle of the floating length and intersection region, the spacing of the sinking or floating warp/weft yarns, the warp/weft yarn spacing, and the return of yarn movement, which are shown in Table 1.

Figure 6(a and b) illustrates a CAD model of a 2 × 1 twill wave fabric with warp/weft skewness angle (δ_1 = 14.48, δ_2 = 14.04), warp/weft return angle (β_1 = 6.17, β_2 = 11.31), and the return of yarn movement (M_{f1}, M_{f2} = 0.054 mm). The warp/weft yarn spacing at the crossover point ($p_{1,i}$ = 0.189 mm, $p_{2,i}$ = 0.249 mm) and the spacing of the sinking or floating warp and weft yarns ($p_{1pi} + c$ = 0.108 mm, $p_{2pi} + c$ = 0.209 mm) are also shown. Therefore, the warp and weft densities were 61.72 ends/cm and 45.1 picks/cm, respectively. The CAD model for the 3 × 1 twill wave fabric is shown in Figure 7(a and b) with warp/weft skewness angle (δ_1 = 6.55, δ_2 = 8.13), warp/weft return angle (β_1 = 5.63, β_2 = 11.31), and the return of yarn movement (M_{f1}, M_{f2} = 0.054 mm). The warp/weft yarn spacing at the crossover point ($p_{1,i}$ = 0.189 mm, $p_{2,i}$ = 0.273 mm) and the spacing of the sinking or floating warp and weft yarns ($p_{1pi} + c$ = 0.135 mm, $p_{2pi} + c$ = 0.235 mm) are also shown such that the warp and weft densities were 62.38 ends/cm and 36.4 picks/cm.

The simulation of 2 × 1 and 3 × 1 twill woven fabrics using the filament assembly model by taking the skewness property into account can demonstrate a wider variety and improve the visual simulation of the real twill woven fabric. The modeled described in this study is based on a homogeneous structure that displays certain differences from the real fabrics, whereas structural parameters in real fabrics change throughout the fabrics [3]. Nevertheless, the data obtained experimentally are very close in terms of control parameters to the skewness property of twill weaves used in the models. It is possible to constitute 3D fabrics simulations used in the study. The 3D CAD geometry modeling of twill woven structures is important because the model is necessary as an input to many computational methods such as modeling of the air permeability or heat transfer for textile fabrics, modeling the mechanical properties of fabrics or their composite parts.

4. Conclusion

CAD modeling with precise geometrical description of woven structures is important because a geometric model is a true visual simulation of real woven fabric and also necessary as an input to many computational models such as those modeling the air permeability or heat transfer or mechanical properties of

Table 1. Input data

Fabric pattern	$d_{1,i}$, $d_{2,i}$ (mm)	d_f (mm)	N_Z (layer)	N_f (filament)	α_1, α_2 (deg.)	θ_1, θ_2 (deg.)	h_1, h_2 (mm)	δ_1 (deg.)	δ_2 (deg.)	β_1 (deg.)
Twill (2 × 1)	0.108	0.012	5	56	25.8, 18.6	30	0.108	14.48	14.04	6.17
Twill (3 × 1)	0.108	0.012	5	56	25.8, 18.6	30	0.108	7.29	8.13	6.17

Fabric pattern	$p_{1,i}$ (mm)	$p_{2,i}$ (mm)	$p_{1pi} + c$ (mm)	$p_{2pi} + c$ (mm)	M_{f1}, M_{f2} (mm)	l_{f1} (mm)	l_{S1} (mm)	l_{f2} (mm)	l_{S2} (mm)	β_2 (deg.)
Twill (2 × 1)	0.189	0.249	0.108	0.209	0.054	0.216	0.502	0.222	0.275	11.31
Twill (3 × 1)	0.189	0.249	0.270	0.422	0.054	0.425	0.502	0.381	0.275	11.31

fabrics. Therefore, the simulated twill woven fabric structures must be improved. This article describes a new computer modeling approach for 2 × 1 and 3 × 1 twill woven fabric structures in which the twill fabrics are formed of asymmetric floatings in which the length of floating sections is not equal on both surfaces. The geometry of twill weaves is defined by taking the skewness property into account. The new algorithms use a filament assembly model in which a single yarn is composed of many filaments by twisting along the crimp shape that according to the real yarn is composed of fibers twisted together. A comparison is made of the new model of 2 × 1 and 3 × 1 twill woven with a single line of yarn path model that includes and excludes the skewness property and also the filament assemble model that excludes the skewness property. The simulation in this study can demonstrate a wider variety of measures to improve the visual simulation of real twill woven fabric.

Nomenclature

$d_{1,i}$, $d_{2,i}$	warp/weft yarn diameters
d_f	filament diameter
d_i^X	coordinate system of yarn in X axis of i_{d2} of warp yarn
d_i^Y	coordinate system of yarn in Y axis of i_{d1} of weft yarn
d_i^Z	coordinate system of yarn in Z axis for warp/weft yarn
$f^X_{Nj}d_i$, $f^Y_{Nj}d_i$, $f^Z_{Nj}d_i$	coordinates of Nth filament of jth layers for i_{di} on X, Y, and Z axis of twill woven fabric structure, respectively
$f^{x'}_{Nj}$, $f^{y'}_{Nj}$, $f^{z'}_{Nj}$	coordinate system of Nth filament in center of yarn at jth layers on x', y', and z' axis, respectively
$g_{\mathrm{pi},i}$	spacing of the arc of the center line yarn at lower segment on XZ or YZ plane
h_1, h_2	warp/weft crimp wave heights
$h_i/2$	warp/weft half crimp
i_{d1}	number of warp yarn in Y axis
i_{d2}	number of weft yarn in X axis
i_X, i_Y	position of the center line of yarn path at the point along the X or Y axis ($i = A, B, C, A$)
$k_{\mathrm{pi},i}$	spacing of the arc of the center line yarn at upper segment on XZ or YZ plane
l_{f1}, l_{f2}	warp/weft, floating length
l_{s1}, l_{s2}	warp/weft intersection length of the intersection region
M_{f1}, M_{f2}	the return of warp/weft yarn movement
N_1, N_2	N_1 or N_2 are number warp/weft in weave repeat, respectively
N_f	number of filament in yarn cross section
N_z	number of layer in yarn cross section
$p_{1,i}$, $p_{2,i}$	warp/weft yarn spacing at the crossover point, respectively
$p_{1\mathrm{pi}} + c$, $p_{2\mathrm{pi}} + c$	warp/weft yarn spacing of the sinking or floating, respectively
R_{jc}	radius of center of yarn at jth layers
$s_{\mathrm{pi},i}$	spacing of the linear part of a center line yarn segment on XZ or YZ plane
θ_1, θ_2	warp/weft crimp angles
α_1, α_2	warp/weft yarn twist angle (degree)
β_1, β_2	warp/weft return angle of the intersection region (degree)
γ	angle of center of each virtual location to the center of yarn
δ_1, δ_2	warp/weft skewness angle of the floating length (degree)

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References

[1] Iyer, K. B., Hepworth, K., Snowden, D. C. (1964). The inherent skewness of the 2/2 twill weave. The Journal of the Textile Institute, 55(1), 99–110.

[2] Turan, R. B., Okur, A. (2013). A 3D model study for 2/1 twill and 3/1 twill weaves. Indian Journal of Fibre & Textile Research, 38(3), 251–258.

[3] Turan, R. B., Başer, G. (2010). Three dimensional computer simulation of 2/2 twill woven fabric by using B-splines. The Journal of the Textile Institute, 101(10), 870–881.

[4] Alamdar-Yazdi, A. (2004). Weave structure and skewness of woven fabric. Research Journal of Textile and Apparel, 8(2), 28–33.

[5] Alamdar-Yazdi, A. (2005). Behaviour of the twill weave woven fabric during relaxation. Fibers and Polymers, 6(4), 306–312.

[6] Konopasek, M., Shanahan, W. J. (1975). A mechanical model of the 2/2 twill weave. The Journal of The Textile Institute, 66(10), 351–357.

[7] Avanaki, M. J., Jeddi, A. A., Rastgoo, A. (2014). Theoretical Estimation of Initial Uniaxial Tensile Modulus in 2/2 Twill Woven Structures. Fibers and Polymers, 15(9), 1992–2000.

[8] Sriprateep, K., Bohez, E. L. J. (2017). CAD/CAE for stress–strain properties of multifilament twisted yarns. Textile Research Journal, 87(6), 657–668.

[9] Sriprateep, K. (2019). CAD/CAE for stress–strain properties of a wide range of multifilament twisted man-made filament yarns. Textile Research Journal, 89(2), 204–215.

[10] Keefe, M., Edwards, D., Yang, J. (1992). Solid modeling of yarn and fibre assemblies. The Journal of the Textile Institute, 83(2), 185–196.

[11] Harwood, R. J., Liu, Z., Grishanov, S. A., Lomov, S. V., Cassidy, T. (1997). Modelling of two-component yarns. Part II: creation of the visual images of yarns. The Journal of the Textile Institute, 88(4), 385–399.

[12] Adanur, S., Liao, T. (1998). 3D modeling of textile composite performs. Composites Part B, 29(6), 787–793.

[13] Goktepe, O., Harlock, S. C. (2002). Three-dimensional computer modeling of warp knitted structures. Textile Research Journal, 72(3), 266–272.

[14] Jiang, Y., Chen, X. (2005). Geometric and algebraic algorithms for modelling yarn in woven fabrics. The Journal of the Textile Institute, 96(4), 237–245.

[15] Sriprateep, K., Pattiya, A. (2009). Computer aided geometric modeling of twist fiber. Journal of Computer Science, 5(3), 221–225.

[16] Patumchat, P., Sriprateep, K. (2019). New computer geometric modeling approach with filament assembly model for woven fabric structures. The Journal of the Textile Institute, 110(1), 50–60.

[17] Sriprateep, K., Singto, S. (2019). New computer geometric modeling approach with filament assembly model for two-ply yarns structures. The Journal of the Textile Institute, 110(9), 1307–1317.

[18] Piegl, L., Tiller, W. (1997). The NURBS book. Springer-Verlag (Berlin/Heidelberg).