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# Computer geometric modeling approach with filament assembly model for 2×2 twill woven fabrics structures

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A new computer geometric modeling approach for 2×2 twill woven fabrics structures has been presented. A 3D model considering their inherent skewness is proposed and can be used in precise geometrical description. Balanced fabric geometry occurs in 2×2 twill weaves where the fabrics are defined by floating and intersecting segments in weaves, which create symmetric floatings on the front and back surfaces of the fabrics. The yarns cross-section of twill woven fabrics uses the concept of virtual locations and each cross-section is rotated along a single yarn path. The curve of each filament in each of two successive cross-sections is approximated by NURBS. The approach described is demonstrated in 3D CAD for twill woven fabrics structures by using the geometric parameters considering their inherent skewness. The simulated twill woven fabrics structures must be improved so that they are a true visual simulation of real twill woven fabrics and can demonstrate wide varieties of form.

**Keywords**: 2×2 Twill weave, Computer-aided design, Filament assembly model, Skewness

## 1 Introduction

A cloth is said to be skew when the average directions of the warp and weft yarns are not perpendicular to each other. Under normal conditions, skewness is commonly found in twill weave structures. The first study on twill weave fabrics which drew attention to thread skewness was carried out by Iyer *et al*.[1] While the yarn skews during long floating regions due to the force applied by other yarns, it skews in the opposite direction during the intersecting motion, and returns to its former position. Thus, balanced fabric geometry occurs in 2×2 twill weaves, where the control polygon of fabrics is defined by the floating and intersecting segments in weaves, which create symmetric floatings on front and back surfaces of fabrics. Turan and Baser[2] carried out visual simulations of 2×2 twill weave woven fabrics on a computer screen. In constructing a preliminary model for the twill weave fabric structure, the yarn paths were divided into small linear segments. The direction angles of yarn central axes was determined using the B-spline method to convert the yarn path to a smooth curve. Turan and Okur[3] also used the B-spline method to obtain visual simulations of 2×1 and 3×1 twill weaves woven fabrics. The inherent skewness of twill fabrics in the floating region has been 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. Avanaki and Jeddi[4] analyzed the 3D geometrical model of 2×2 twill woven structures with consideration of the straight-line geometry for yarn path and circular geometry for yarn cross-section and their inherent skewness in their fully relaxed state. Also, Avanaki *et al*.[5] presented a theoretical analysis for predicting the tensile modulus of 2×2 twill woven fabrics. The proposed theory was compared and validated with some experimental data.

Knowledge of the geometry of a fabric structure provides valuable information to both manufacturers and designers, while enabling the prediction of the properties and in-use behavior of the product. To simplify the yarn-structure simulation, the previous works regarding geometrical modeling of yarn structure were based on a single line yarn path[6-10] which enabled development of models to display the

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visual characteristics of real yarns for modeling ply yarns structure, woven fabrics, twill weave woven fabrics and knitted fabrics. Therefore, the presentations were limited to virtual representation and prediction of the properties. The filament assembly model[11-14] had developed a CAD model of yarn as an assembly of many filaments by twisting. For the prediction of the tensile properties, researchers[15,16] successfully used a CAD/CAE model with a filament model to predict the stress-strain curves of yarn structures.

Consequently, the aim of this study is to construct a three-dimensional geometrical model of twill weave woven fabrics with a filament assembly model using CAD. A 3D geometrical model considering their inherent skewness has been proposed and can be used in precise geometrical description of 2×2 twill woven structures. Examples of twill weave woven fabrics structures with inherent skewness are demonstrated.

## 2 Materials and Methods

The major steps for constructing the model are shown in Fig. 1. The geometric parameters input to the model are the same, as also reported by Patumchat and Sriprateep[13] ($d_{1,i}$, $d_{2,i}$ , $p_{1,i}$,$p_{2,i}$, $h_1$,$h_2$, $\theta_1$, $\theta_2$, $\alpha_1$,$\alpha_2$, $d_f$, $N_f$, and $N_z$). 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 ($\delta_1$, $\delta_2$), warp/weft return angle of the intersection region ($\beta_1$ , $\beta_2$) and the return of yarn movement ($M_{f1}$, $M_{f2}$). The proposed new algorithm has three main parts, namely the first describes the 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 a 3D model in warp/weft yarn, and the third part contains the CAD model.

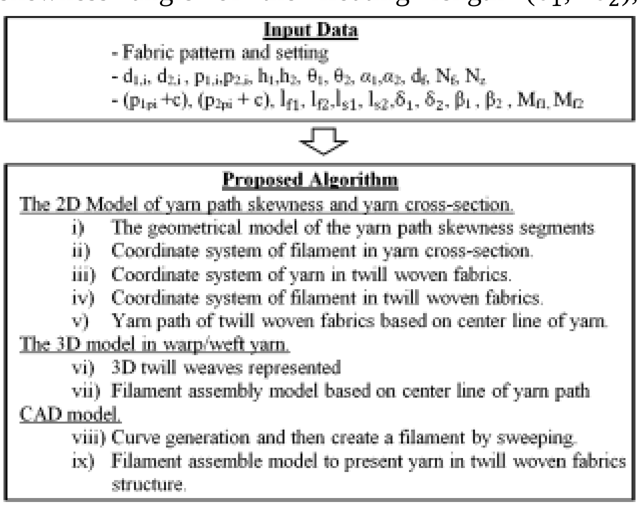


Fig. 1 — Major steps of computer modelling approach for constructing a 3D twill woven fabrics [d1,i, d2,i = warp/weft yarn diameters; p1,i, p2,i = warp/weft yarn spacing at the crossover point; h1, h2= warp/weft crimp wave heights; θ1, θ2 = warp/weft crimp angles; α1 , α2 = warp/weft yarn twist angle (degree); df = filament diameter; Nf = number of filament in yarn cross-section; and Nz= number of layer in yarn cross-section]

### 2.1 2D Model of Yarn Path Skewness and Yarn Cross-section

#### *2.1.1 Geometrical Model of Yarn Path Skewness Segments*

Figure 2 shows the coordinate system of the filaments in the yarn cross-section and woven fabrics structure for a 2x2 twill weave. Figures 2 (a) and (b) show the origin point of the 2D model (X = 0, Z = 0) of the yarn, being perpendicular to each other in the woven fabrics structure in the X, Z axes. Some of the woven fabrics parameters, such as number of warp/weft yarn ($i_{d1}$, $i_{d2}$), spacing of the warp and weft yarns at the crossover point ($p_{1,i}$, $p_{2,i}$), spacing of the sinking or floating warp, and weft yarns in the weave fabrics structure ($p_{1pi}$, $p_{2pi}$), are also shown in the figure. In this study, a geometrical model considering their inherent skewness has been proposed, which can

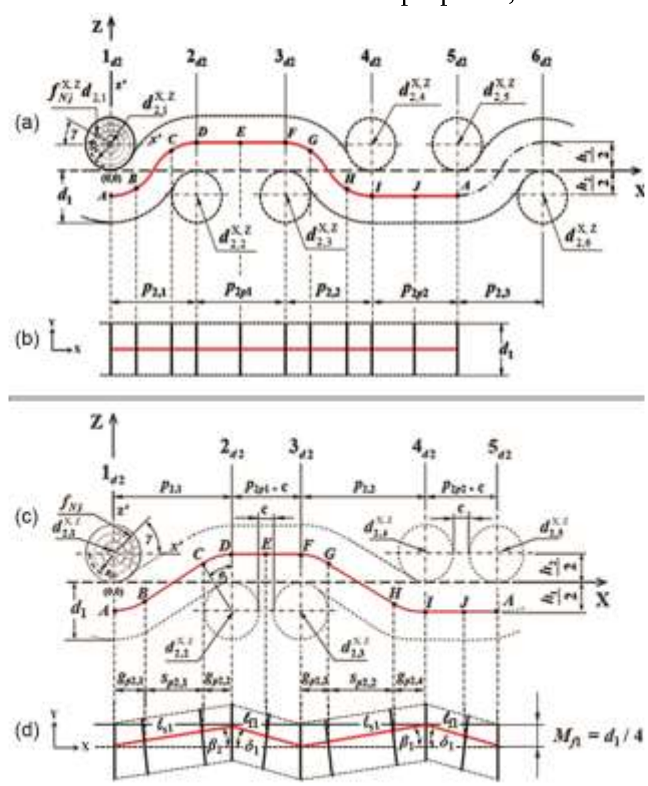


Fig. 2 — Coordinate system of filaments in 2×2 twill woven fabrics and the projection linear yarn path of floating and intersecting region [(a&b) the yarns are perpendicular to each other($\beta = 0, \delta = 0$) and (c&d) the inherent skewness of yarns]

be used in precise geometrical description of twill woven structures. The characteristic property of twill weaves is that the warp/weft floatings are not perpendicular, but form an angle. Figures 2(c) and(d) show the coordinate system of filaments in yarn cross-section for 2×2 twill weave fabrics structure and the linear yarn path skewness of the unit weave length ($p_r$). The unit weave length is defined in Eq. (1) as related to the projection length of the 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, and the intersection line makes an angle β with the y axis and the warp and weft settings of the fabrics ($S_1$, $S_2$) respectively. In the equations, subscripts 1 and 2 refer to parameters in the warp and weft directions respectively.

In the case of 2×2 twill weave, the unit weave length consists of two floating and two intersecting segments. This length is theoretically related to the density of yarns in the fabric structure and referring to Figs 2 (c) & (d), it is given by the following equation:

$$pr_1 = \frac{4}{S_2} = 2l_{f1}cos\delta_1 + 2l_{s1}cos\beta_1 \qquad \ldots(1)$$

where $pr_1$ is the length of weave unit which consists of two floating and two intersecting segments; $S_2$, the weft setting of the fabric; $l_{f1}$, the warp floating length; and $l_{s1}$, the warp intersection length of the intersection region. 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[4]. In this study, we used the values of free space (c) between the two yarns over the floating region. For 2×2 twill weave, the floating length of warp yarn in the floating region can be estimated as follows:

$$l_{f1} = \frac{p_{2pi}+c}{cos\delta_1} \qquad \ldots(2)$$

where $p_{2pi} + c$ is the weft yarn spacing of the floating; $\delta_1$, the warp skewness angle of the floating length. The intersecting length of warp yarn can be estimated as follows:

$$l_{s1} = \frac{p_{2,i}}{cos\beta_1} \qquad \ldots(3)$$

Where $p_{2,i}$ is the weft yarn spacing at the crossover point; and $\beta_1$, the warp return angle of the intersection region.

In the input data, the skewness angle (δ, β), the floating length ($\ell_f$) and the intersecting length ($l_s$) were determined using Eqs(1)-(3). 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:

$$M_{f1} = M_{f2} = d_i/4 \qquad \ldots(4)$$

where $d_i$ is the yarn diameter; $M_{f1}$ and $M_{f2}$, the return of warp/weft yarn movement.

***2.1.2 Coordinate System of Filament in Yarn Cross-section***

To simulate the filament distributions in yarn cross-section of twill woven fabrics, the concept of virtual location is used. In this study, we used the same parameters as in a previous study[13]. Therefore, the Cartesian coordinates from polar coordinates of the center of yarn to coordinate system $x'z'$ are:

$$f_{Nj}^{x'} = R_{jc}cos\gamma;\ f_{Nj}^{z'} = R_{jc}sin\gamma \qquad \ldots(5)$$

And also, the coordinate system $y'z'$ are:

$$f_{Nj}^{y'} = R_{jc}\,cos\gamma;\ f_{Nj}^{z'} = R_{jc}\,sin\gamma \qquad \ldots(6)$$

where $f_{Nj}^{x'}$, $f_{Nj}^{y'}$ and $f_{Nj}^{z'}$ are the coordinates system of $N^{th}$ filament in center of yarn at $j^{th}$ layers on $x'$, $y'$ and $z'$ axis, respectively; $R_{jc}$, the radius of centre of yarn at $j^{th}$ layers; and $\gamma$ , the angle of center of each virtual location to the center of yarn.

***2.1.3 Coordinate System of Yarn in Twill Woven Fabrics***

For 2×2 twill weave fabrics structure, the position of the center fabrics structure is characterized by Cartesian coordinate (X, Z) of the center of twill woven fabrics structure (X = 0, Z = 0) that is shown in Fig. 2 (c). In 2D twill weave, number of warp/weft yarn in X/Y axis were defined as $i_{d1}$ (1, 2…$N_1$) or $i_{d2}$(1, 2…$N_2$), where $N_1$ and $N_2$ are number of warp/weft in the weave repeat respectively. The subscripts 2i and 2i+1 represent the values of an even number and an odd number respectively. Therefore, the coordinate of center of yarn at $i_{d2}$ in X axis is defined as:

$$d_{i=2i}^{X} = (p_{2pi}+c)\left[\left(\frac{i_{di=2i}}{2} - 1\right)\right] + p_{2,i}\left(\frac{i_{di=2i}}{2}\right);\ 2i = 2, 4, 6\ldots N_{2d2} \qquad \ldots(7)$$

and

$$d_{i=2i+1}^{X} = (p_{2pi}+c)\left[\left(\frac{i_{di=2i+1}}{2} - 0.5\right)\right] + p_{2,i}\left[\left(\frac{i_{di=2i+1}}{2} - 0.5\right)\right];\ 2i+1 = 1, 3, 5\ldots N_{2d2} \qquad \ldots(8)$$

where $d_i^X$ is the coordinate system of yarn in X axis of $i_{d2}$ of warp yarn; $i_{d1}$, the number of warp yarn in Y axis; and $i_{d2}$, the number of weft yarn in X axis.

The number of warp yarn in Y axis, and the coordinate of center of yarn at $i_{d1}$ are defined in the same way as in Eqs (7) and (8). The position of the center fabrics structure is characterized by Cartesian coordinate (Y, Z) of the center of the twill woven fabrics structure (Y = 0, Z = 0).

In this study, we used the crimp values in the Z axis derived from the linear segmented model of yarn path of twill structure. These curvilinear movements will form cubic curve segments of the model and the position of the yarn path in Z axis is accepted as the fabrics thickness direction. The crimp height $h_i$ of the crimp weave can be calculated for $h_i/p_i$ values. The Cartesian coordinate (X, Z) or (Y, Z) of the center of twill woven fabrics structure can be separated into two parts, as shown in Fig. 2. The first part was defined as positive (+) $h_i/2$ and the second part was defined as negative (–) $h_i/2$. The coordinate of $h_i/2$ in Z axis is defined as:

$$d_i^Z = \pm h_i/2$$

$$\begin{cases} \frac{h_2}{2}; \text{where coordinate of yarn in upper quadrant regions} \\ -\frac{h_2}{2}; \text{where coordinate of yarn in lower quadrant regions} \end{cases} \quad \ldots(9)$$

where $d_i^Z$ is the coordinate system of yarn in Z axis for warp/weft yarn; and $h_i/2$ , the warp/weft half crimp.

***2.1.4 Coordinate System of Filament in Twill Woven Fabrics***

The coordinate system $(x', z')$ or $(y', z')$ of filament in yarn cross-section is defined in Eqs (5) and (6) and the coordinate system (X, Z) or (Y, Z) of yarn in woven fabrics structures is calculated with Eqs (7) - (9). So that, the coordinates of $N^{th}$ filament of $j^{th}$ layers for $i_{d2}$ on X axis ($f_{Nj}^X d_i$), $i_{d1}$ on Y axis ($f_{Nj}^Y d_i$) and Z axis ($f_{Nj}^Z d_i$) that are perpendicular to the twill woven fabrics structure is shown hereunder. The positions of the filaments in yarn cross-section of $i_{d2}$ in X axis is defined as:

$$f_{Nj}^X d_i = d_i^X + R_{jc}\cos\gamma$$
$$\text{Or} = d_i^X + f_{Nj}^{x'} \quad \ldots(10)$$

and the positions of the filaments in yarn cross-section of $i_{d1}$ in Y axis is defined as:

$$f_{Nj}^Y d_i = d_i^Y + R_{jc}\cos\gamma$$
$$\text{or} = d_i^Y + f_{Nj}^{y'} \quad \ldots(11)$$

The positions of filaments in twill woven fabrics of $i_{d1}$ or $i_{d2}$ in Z axis is defined as:

$$f_{Nj}^Z d_i = \pm h_i/2 + R_{jc}\sin\gamma$$
$$\text{or} = d_i^Z + f_{Nj}^{z'} \quad \ldots(12)$$

where $f_{Nj}^X d_i$, $f_{Nj}^Y d_i$ and $f_{Nj}^Z d_i$ are the coordinates of $N^{th}$ filament of $j^{th}$ layers for $i_{di}$ on X, Y and Z axis of twill woven fabric structure respectively; $and\ d_i^Y$, the coordinate system of yarn in Y axis of $i_{d1}$ of weft yarn.

**2.2 3D Model in Warp/Weft Yarn**

***2.2.1 3D Twill Weaves Representation***

In twill woven fabrics, the floats and intersections of the warp/weft yarns are not perpendicular to each other due to the effect of internal forces developing during formation of the fabric. In 2×2 twill weave, warp/weft yarns make four curvilinear movements along the twill weave unit, two of them floating, the other two intersecting that shows the center line of yarn path for connected points (A, B, C…A) on XZ axis in Figs 2 (d) and 3. The main dimensionless parameters in the floating region are $p_{2pi}$ +c and in the intersecting region are $p_{2,i}$ ($g_{p2,i} + s_{p2,i} + g_{p2,i+1}$) that are the spacing of center line of yarn at the connected points on the XZ plane. The center line of yarn path makes an angle by skewing in the floating region ($\delta_i$), and then it makes an angle in the intersecting region ($\beta_i$) of the linear part of yarn segment. $\theta_i$ is the crimp angle of the yarn.

The mathematical expression of woven fabrics structures that enabled the automatic generation of 2D and 3D weaves represented by 2D binary matrices to a general vector matrix was developed by Jiang and Chen[10]and the study was extended by Patumchat and Sriprateep[13]. They used the element wave matrix from the position of the crossover point to the connected points of the relevant piecewise of the arc abscissa models. In this study, we used the element vectors for 2×2 twill weave having connected points (A, B, C…A) [Fig. 3] in the center line of the yarn path along the yarn length. The fabrics pattern and setting were designed, in such a way that the structure of the initial vector matrix $H_0$ of the deflection of the yarns can be obtained. The structure of one unit cell for 2×2 twill weave woven fabrics, the number of the connected points of the piecewise for the arc abscissa models in warp direction are 11 points and weft directions are 11 points. The data points of the coordinates $x_i$, $y_i$, $z_i$ of the crimp weave in each cross-section are along the centerline of the yarn path that is perpendicular to the centerline yarn path. For

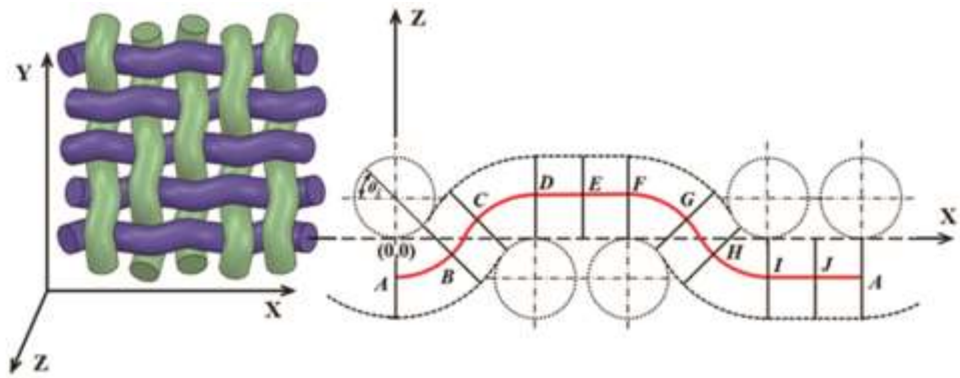


Fig. 3 — Projection on plane XZ

example, the fabrics pattern and setting were designed, so the structure of the initial vector matrix $H_0$ in the floating region in warp or weft ($A_{1or2}$, $D_{1or2}$, $F_{1or2}$, $I_{1or2}$, $A_{1or2}$) of the yarns can be obtained as shown below:

$$H_0 = \begin{bmatrix} \vec{T}_{A1,D2} \vec{T}_{D1,A2} \vec{T}_{F1,I2} & \vec{T}_{I1,F2} & \vec{T}_{A1,D2} \\ \vec{T}_{D1,A2} & \vec{T}_{F1,I2} & \vec{T}_{I1,F2} \vec{T}_{A1,D2} \vec{T}_{D1,A2} \\ \vec{T}_{F1,I2} & \vec{T}_{I1,F2} \vec{T}_{A1,D2} \vec{T}_{D1,A2} & \vec{T}_{F1,I2} \\ \vec{T}_{I1,F2} & \vec{T}_{A1,D2} \vec{T}_{D1,A2} \vec{T}_{F1,I2} & \vec{T}_{I1,F2} \\ \vec{T}_{A1,D2} \vec{T}_{D1,A2} \vec{T}_{F1,I2} & \vec{T}_{I1,F2} & \vec{T}_{A1,D2} \end{bmatrix} \quad \ldots (13)$$

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

#### *2.2.2 Filament Assembly based on Center Line of Yarn Path*

The projected radius of the crimp weave at the first layer ($R_{jc}$ = 0) based on center line of yarn in twill woven fabric structure were explained in the previous section. The 3D geometrical model considering the center line yarn paths were divided into small linear segments and 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. Each yarn cross section is perpendicular to the centerline yarn path along the yarn length. The data points of coordinate $x_i$, $y_i$, $z_i$ of crimp weave in each cross-section can be obtained in vector matrix $H_0$. The filaments in outer layers are arranged with open packing form using the virtual locations concept and each layer follows the filaments in center along the length of yarn path. In 2×2 twill weave, the projection of outer layers $(x', z')$ of filament in yarn cross-section is defined in Eqs(5)&(6) and the coordinate system (X, Z) of yarn in woven fabrics is calculated using Eqs(7)-(9). Therefore, the positions of filaments in woven fabrics of $i_{d2}$ in X and Y axis is defined by Eqs(10)&(11). The positions of filaments of $i_{d2}$ in Z axis are defined using Eq. 12. The coordinate system $(y', z')$ of filament in yarn cross-section and coordinate system (Y, Z) of yarn in twill woven fabrics are calculated in the same way, but using different axes. In each cross-section, the filament in the first layer follows the center line of yarn, and then each cross-section is rotated along the yarn length by a pre-determined amount in respect of the previous one allowing for the yarn twist. In the case of twill woven fabrics, the center line of yarn path makes an angle by skewing in the floating region ($\delta_i$), and then it makes an angle in the intersecting region ($\beta_i$) of the linear part of yarn segment on the XZ or YZ plane. The coordinate of filaments in each cross -section on the normal plane of centerline of yarn, therefore, in warp direction along the yarn length ($x_i$) will be at ($y_i$, $z_i$) and the filament in weft direction along the yarn length ($y_i$) will be at ($x_i$, $z_i$). Therefore, the projection of the filaments with their inherent skewness in outer layers of warp/weft directions can be calculated using the following equations:

**For warp:**

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

**For weft:**

$$\begin{cases} x' = x_i + [R_{jc}\cos(\gamma+\psi)\cos\theta_i]/\cos(\delta_i)\cos(\beta_i) \\ y' = y_i - R_{jc}\sin(\gamma)\sin\theta_i \\ z' = z_i + R_{jc}\sin(\gamma+\psi)\cos\theta_i \end{cases} \quad \ldots(14)$$

In this equation, an angle by skewing in the floating region ($\delta_i$), that is the angle in the intersecting region ($\beta_i$), is zero degree. Also, the angle by skewing in the intersection region ($\beta_i$), that is the angle in the floating region ($\delta_i$) is zero degree. An example of modeling fibre assemblies is shown in the next section.

### 2.3 CAD Model of Twill Woven Fabrics Structure

The data points of coordinates $x_i$, $y_i$, $z_i$ can be obtained in vector matrix $H_0$ and the projection of the filaments in outer layers of warp or weft directions $(x', y', z')$ can be calculated using Eq.14. In the case of twill woven fabrics and considering the inherent skewness, the filament curve in each interval between two successive cross-sections can be approximated by a cubic rational B-spline curve (cubic NURBS curve). NURBS curves are parametric splines, whose main components are the 2D or 3D control points or control vertices, the weights of these points, and a knot vector limiting the effect of the control vertices onto a given segment of the curve. The basic functions can be defined by the Cox-de Boor recursion formula. Given data points are $\vec{T}_{a1,a2}(t)$ for the centerline of yarn path and $\{d_i\}$ of coordinate $x', y', z'$ of the filaments in each cross-sections, and associating parameters $\{\vec{r}(t)\}$, i = 0, 1,...., m. Piegl and Tiller[17] is defined the approximation curve in the least squares sense, as shown below:

$$\text{Minimize } \sum_{i=0}^{m} \left\| d_i - \vec{r}(t) \right\|^2 \qquad \ldots(15)$$

The user specifies the points and the curve to pass this point as closely as possible. The filaments paths in each interval between two successive cross - section are approximated by NURBS curves. Each fibre is created by sweeping a closed curve along a centerline path. Yarn structures can be represented in solid model.

## 3 Results and Discussion

In this study, the skewness property of 2×2 twill weaves and structure parameters have been taken into consideration while modeling the 3D geometry of the fabrics. The CAD model used the filament assembly model for modeling the twill fabrics structures. In previous work, Turan and Baser[2] used the B-spline method for modeling the 2×2 twill fabrics structures. They considered the yarn to be solid and constant along the yarn path with uniform-structured monofilament. Experimental fabrics of 2×2 twill weave woven from double yarns were used to obtain calculated values for yarn diameter and also the value of fabrics thickness due to warp amplitude. The suitability and feasibility of the model developed is the visual examination of the 3D simulation of fabrics surface appearance on the computer screen. As skew angles smaller than 6º gives simulations (for some of the fabrics), showing thread surface intersections, the skew angles of 6º, 8º, and 12º for both warp and weft floats are tried. The statistical results show that the structural parameters of the real twill fabrics could be predicted by using the outputs of this geometrical model. The input parameters to the model are shown in Table 1. Figure 4 illustrates a model of a twill fabric structure with a single line of yarn path, for which the cross-sections of the warp and weft yarn are both circular, with the diameter being 0.108 mm. The fabric simulations are close, in terms of the skewness property of twill weave, to those used by Turan and Baser[2]. This study uses the warp/weft skewness angle ($\delta_1$, $\delta_2$ = 11.47º), warp/weft return angle ($\beta_1$, $\beta_2$ = 8.21º) and the return of yarn movement ($M_{f1}$, $M_{f2}$ = 0.027 mm). The warp and weft density being 62.27 ends/cm and 62.27 picks/cm respectively. However, the presentations are limited to virtual representation and prediction of the properties.

Figure 5 reports 3D computer simulations of 2×2 twill weaves fabrics with the filament assembly model in different views that excludes the skewness property[13]. The input parameters of each woven fabrics structure for the yarn diameter in the warp/weft are 0.108 mm and filament diameter are 0.012 mm. The yarn spacing at the cross-over point of the warp/weft is 0.187 mm and haft crimp weave height is 0.108 mm. The number of layers in the yarn cross- section is 5 and the number of filaments is 56.

Table 1 — Input data

| Fabric pattern (2x2 twill) | $d_{1,i}$, $d_{2,i}$ | $d_f$ | $N_Z$ | $N_f$ | $\alpha_1$, $\alpha_2$ | $\theta_1$, $\theta_2$ | $h_1$, $h_2$ | $\delta_1$, $\delta_2$ | $p_{1,i}$ | $p_{2,i}$ | $p_{1pi+C}$ | $p_{2pi+C}$ | $M_{f1}$, $M_{f2}$ | $\ell_{f1}$, $\ell_{f2}$ | $\ell_{S1}$, $\ell_{S2}$ | $\beta_1$, $\beta_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | mm | mm | layer | filament | deg | deg | mm | deg | mm | mm | mm | mm | mm | mm | mm | deg |
| Single yarn path | 0.108 | - | - | - | - | 30 | 0.108 | 11.47 | 0.187 | 0.187 | 0.133 | 0.133 | 0.027 | 0.135 | 0.189 | 8.21 |
| Filament assemble | 0.108 | 0.012 | 5 | 56 | 35.75 | 30 | 0.108 | - | 0.187 | 0.187 | 0.187 | 0.187 | - | - | - | - |
| Skewness I | 0.108 | 0.012 | 5 | 56 | 35.75 | 30 | 0.108 | 11.47 | 0.187 | 0.187 | 0.133 | 0.133 | 0.027 | 0.135 | 0.189 | 8.21 |
| Skewness II | 0.074, 0.108 | 0.012 | 4,5 | 36, 57 | 39.08, 29.77 | 45, 33.73 | 0.152, 0.108 | 9.28, 11.82 | 0.167 - | 0.167 - | 0.113 - | 0.129 - | 0.0185, 0.027 | 0.115, 0.132 | 0.168, 0.168 | 6.32, 9.24 |

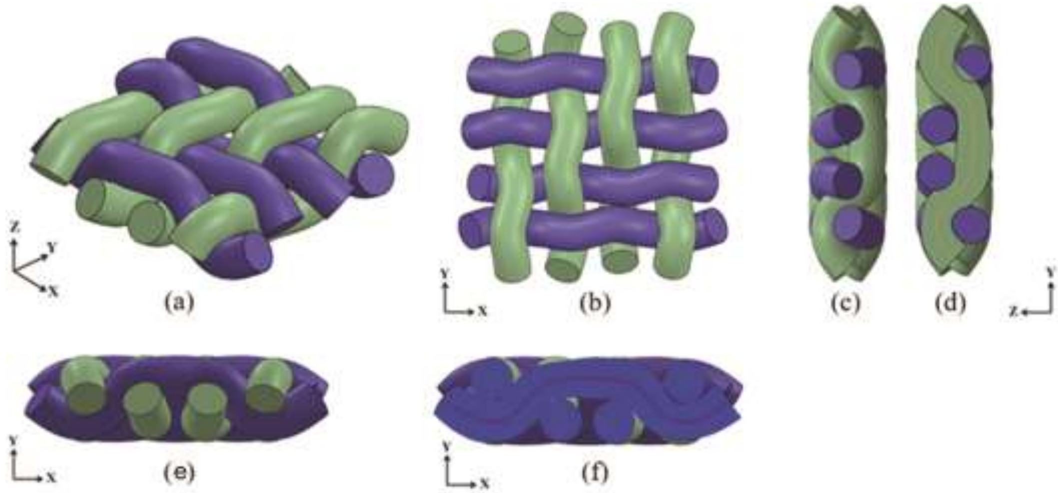


Fig. 4 — Thread model and 3D image of 2/2 twill fabrics structure with a single line of yarn path (a) isometric view, (b) top view, (c) side view, (d) cross-section at center line of yarn path for weft yarn, (e) front view, and (f) cross-section at center line of yarn path for warp yarn[2]

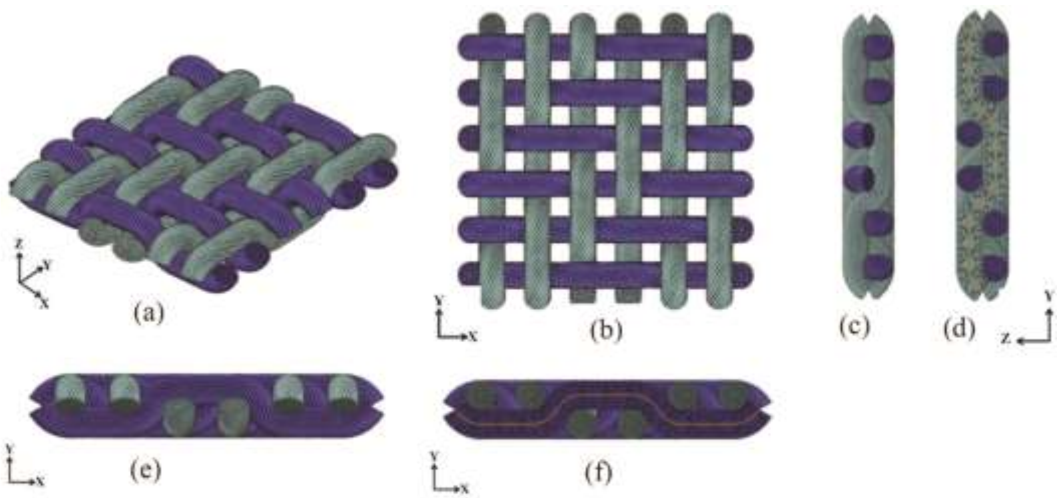


Fig. 5 — CAD of 2x2 twill weave fabrics(a) isometric view, (b) top view, (c) side view, (d) cross-section at center line of yarn path for weft yarn, (e) front view, and (f) cross-section at center line of yarn path for warp yarn[13]

The twist angle of each yarn structure is $35.75^0$. The spacing of the sinking or floating warp/weft yarns in the weave fabrics structure is 0.108 mm. Therefore, the warp and weft densities are 53.48 ends/cm and 53.48 picks/cm respectively.

In the case of the twill fabrics which includes the skewness property, the weave fabrics structure depends on the fabrics pattern and setting. Additional parameters consist of the warp/weft skewness angle of the floating length, warp/weft return angle of the intersection region, warp/weft yarn spacing, the spacing of the sinking or floating warp/weft yarns and the return of yarn movement. The major steps for constructing our new three-dimensional model for twill woven fabrics are shown in Fig. 1. Figure 6 shows a CAD model of 2×2 twill weave fabrics with the same control parameters, especially the skewness property of twill weave as described by Turan and Baser[2]. The number of layers in the yarn cross-section is 5 and the number of filaments is 56. The twist angle of each yarn structure is $35.7^o$. We used the warp/weft skewness angle ($\delta_1$, $\delta_2$ = $11.47^o$), warp/weft return angle ($\beta_1$, $\beta_2$ = $8.21^o$), the return of yarn movement ($M_{f1}$, $M_{f2}$ = 0.027 mm), the warp/weft yarn spacing at the crossover point ($p_{1,i}$, $p_{2,i}$ = 0.187 mm.) and the spacing of the sinking or floating warp and weft yarns [($p_{1pi}$ + c, $p_{2pi}$ + c) = 0.133 mm] are the same parameter in the warp/weft direction. Therefore, the warp and weft densities are 62.27 ends/cm and 62.27 picks/cm respectively.

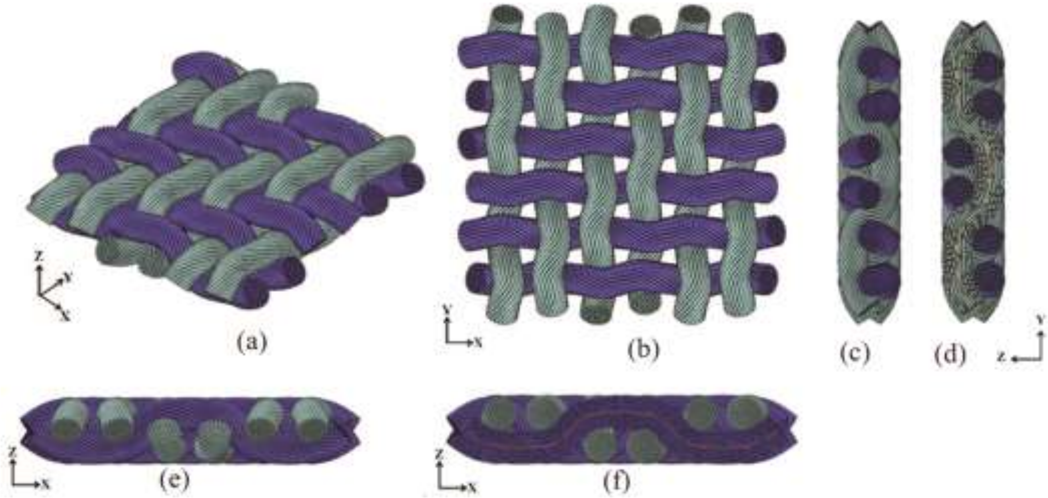


Fig. 6 — CAD of 2×2 twill weave fabrics with skewness property (a) isometric view, (b) top view, (c) side view, (d) cross-section at center line of yarn path for weft yarn, (e) front view, and (f) cross-section at center line of yarn path for warp yarn

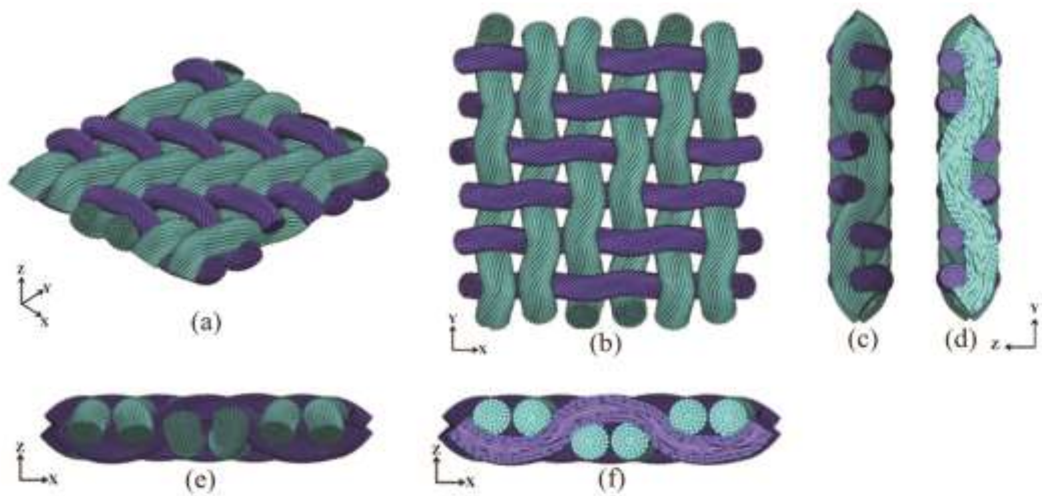


Fig. 7 — CAD of 2×2 twill weave fabrics with skewness property (a) isometric view, (b) top view (c) sideview, (d) cross-section at center line of yarn path for weft yarn, (e) front view, and (f) cross-section at center line of yarn path for warp yarn

Figure 7 shows a CAD model of a 2×2 twill weave fabrics which has different diameters of yarn cross-section. The warp yarn diameter (d1) is 0.074 mm of 4 layers. Each filament diameter is 0.012 mm. The yarn is composed of 36 filaments with a $39.08^0$ twist angle. The weft yarn diameter (d2) is 0.108 mm of 5 layers. Each filament diameter is 0.012 mm. The yarn is composed of 57 filaments with a $29.77^0$ twist angle. Additional parameters consist of the warp/weft skewness angle ($\delta_1$ = 9.28º, $\delta_2$ = 11.82º), warp/weft return angle ($\beta_1$= 6.32º, $\beta_2$ = 9.24º), the return of yarn movement ($M_{f1}$ = 0.0185, $M_{f2}$ = 0.027 mm), the warp/weft yarn spacing at the crossover point ($p_{1,i}$, $p_{2,i}$ = 0.167 mm) and the spacing of the sinking or floating warp and weft yarns ($p_{1pi}$ + c = 0.113, $p_{2pi}$ + c = 0.129 mm) are the same parameter in the warp/weft direction. Therefore, the warp and weft densities are 72.59 ends/cm and 72.59 picks/cm respectively.

Figures 4-6 show a comparison between a single line of yarn path model[2], the filament assembly model that excludes the skewness property[13] and the filament assemble model by taking the skewness property into account which is created using the method described in this study. The fact is that, real yarn is composed of many fibres twisted together and that a 3D visual simulation with a filament assembly model presents quite an analogous view with photographs of real fabrics. Due to the concept of visual location in each yarn cross-section, each filament in yarn structures could be obtained without overlapping in yarn structure and may be considered as an improvement on the previous work[18]. It is very natural that the modeled fabrics display certain differences from the real fabrics, as the model is based on a homogeneous structure, whereas structural parameters in real fabrics change throughout the fabrics[3]. However, experimental data obtained are very close in terms of control parameters used in the study[2]. Especially, the skewness property of twill weaves used in the models makes it possible to constitute 3D fabrics simulations. Consequently, it can be concluded that the filament assembly model with skewness property developed is satisfactory in describing the 3D structure and also can demonstrate a wider variety and improve the visual simulation of the real 2×2 twill weave fabrics. Besides, these models could be used as an input to many computational models, such as modeling the mechanical properties of fabrics, composite parts and their damage behavior for use in engineering applications, and also the modeling of the heat transfer.

## 4 Conclusion

This study describes a computer modeling approach for three-dimensional2×2twill woven fabrics structures. The geometry of twill weaves is defined by taking the skewness property into account. The fact is that the real yarn is composed of many fibres twisted together, therefore the new algorithms have a filament assembly model with skewness property in which a single yarn is composed of many filaments by twisting along the crimp shape. The simulated twill woven fabric structures must be improved so that they are a true visual simulation of real twill woven fabrics and can demonstrate wide varieties or forms. Also, the 3D CAD with filament assembly model for twill structures could be obtained without overlapping filament surfaces in yarn structure due to our use of the concept of visual location in each yarn cross-section. Besides, these models could be used as an input to many computational models, such as modeling the mechanical properties or heat transfer of fabrics and composite parts.

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