A dynamic weaving simulator for filament-level 3D woven fabric modelling

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Abstract
A dynamic textile weaving simulator is established to connect weaving actions to fabric patterns and microstructures. It utilizes the Digital Element Approach (DEA) under the framework of the software package Digital Fabric and Composite Analyser (DFCA). The key components of a Jacquard loom are explicitly modelled utilising the ‘hole/no hole’ principle. Yarn interlacing motion is guided by weaving matrix specified by steps. Shedding, weft insertion, beat-up, and take-up actions are modelled and explained. The inter-fibre contact force, fibre forces (tensile, shear, and bending), and boundary conditions in the weft direction are considered. The weaving process of five cells in the warp direction of a 10-layer 3D orthogonal woven fabric is simulated at the filament level to derive for its microstructure. The results show that the fabric microstructure continues to change after being woven, and the thickness and length of each individual cell decrease with further weaving steps. The microstructures of newly woven cells converge after the weaving of two further cells in the lengthwise direction. The microstructure of the second

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cell closely matches that of an actual weaved fabric, as evaluated by microscopy images. Penetration occurs between adjacent weft yarns in the same column, which fundamentally changes their microstructure, composition, and material properties. Parametric studies show that the ratio of binder to warp yarn tension determines the fabric thickness. Increases in the take-up length and binder yarn tension lead to a decrease and increase in the reed tension, respectively. This work provides valuable insights into fabric design and manufacture instruction.

**Keywords**
Fabrics, textiles, microstructures, process simulation, weaving

**Introduction**
Fibre-reinforced polymer composites comprise aligned, random, or woven fibres in a polymeric matrix. Of the common geometries, woven fabric-reinforced composites, wherein the fabric comprises high-performance fibres, are commonly used in applications that require durability in aggressive environments. To achieve deep-level exploitation for use in engineering applications, modelling of the fabric’s microgeometry and mechanical response is crucial.

The fibre architecture of woven fabrics has a profound effect on their mechanical properties. Research to characterise these microstructures has been ongoing for decades through experimental, analytical, numerical, and combined approaches. Experimental approaches work in the most intuitive manner; the fabric structure is analysed from computed tomography (CT) scans and cross-sectional microscopy images of the textile specimens, with the individual tow information identified through image recognition techniques. Analytical methods work in a similar manner; geometrical modelling is conducted from CT scans by identifying geometric parameters such as the width and thickness of warp and weft yarns and the distance between adjacent yarns, with idealised assumptions on yarn path (mostly as sinusoidal functions) and cross-sectional shapes. However, the success of both methods is highly dependent on the target specimen, and it is inherently difficult to characterise the sub-yarn-level structure.

To compensate for the deficiencies of the aforementioned methods, computer modelling has emerged as a popular and powerful tool for fabric geometry and related parametric studies. One key commercial software for modelling textile structure is TexGen, which was first developed by the University of Nottingham in 1998. Other similar software includes WiseTex and TechText CAD. TexGen uses the weave type and yarn spacing, width, height, cross-sectional shape, and maximum volume fraction as inputs to automatically calculate the geometry of the fabric unit cell. The yarn path is represented by splines (e.g. cubic Bezier spline, natural cubic splines, and periodic cubic splines) defined piecewise by polynomials. Because the generated geometry information can be easily exported for use in commercial finite element (FE) software, this method is conveniently available for studies on textile mechanics, permeability, and
composite mechanical behaviour. However, it assumes that the yarn cross-section has a constant shape, and that the cross-section is the same for all yarns of the same type, which is not the case for most weave types.

Filament-level fabric modelling aimed at achieving variant yarn cross-sections has become a research focus in recent years. Patumchat et al. initiated a filament assembly model for plain- and twill-weave fabrics by twisting along the crimp shape based on the classic Peirce’s model. Liu et al. and Xie et al. proposed a filament-level 2D plain-weave fabric model based on given geometric parameters. In these approaches, the spatial path of either the virtual fibre or yarn is defined by a sine function, and the fabric microstructure is quantified rather than predicted. In recent years, Ying et al., Hu et al., Pierreux et al., Durville et al., Daelemans et al., and Green et al. have presented approaches for generating unit-cell models of 3D woven fabrics with variant yarn cross-sections under the framework of commercial FE software. Fibre bundles are initially positioned in an idealised loose state, and then gradually and automatically shaped by tensioning, separation, thermal expansion, and transverse compaction mechanisms. Yang et al. made the next advance by generating a 3D woven fabric model through weft insertion and yarn interlacing. The simulated fabric unit cell was then placed between two rigid plates to compress it to the thickness of the corresponding specimen. However, because excessive contact occurs between fibres in the same tow and between tows, generating a fabric piece using finite element method (FEM) is either computationally too expensive or requires accuracy to be sacrificed.

In contrast to the above-mentioned numerical methods, Wang et al. initiated the digital element concept (DEA) in 2001 and developed it into a dynamic relaxation approach with periodic boundary conditions utilising the explicit central difference numerical algorithm. In this approach, one virtual fibre is composed of short-rod elements connected by a torsional spring. Fibre bending is not preserved by the element itself but by elements with joints. In addition, a homemade software package Digital Fabric and Composite Analyser (DFCA), with yarn discretisation, which splits yarns into a user-defined number of virtual fibres with equal cross-sectional areas, and fibre discretisation, which divides virtual fibres into several rod elements, has been implemented to adjust fabric resolution. Thus, the computational efficiency problem is controlled. It should be noted that most approaches claim that the overall fabric microstructure is well represented by discretising each yarn into 19 virtual fibres.

Although accurate modelling of the fabric microgeometry can be achieved through filament-level modelling methods, the relations between weaving actions, fabric patterns, and microstructures are seldom qualitatively and quantitatively discussed.

In this study, a dynamic weaving simulator that fully models loom kinetics and kinematics is proposed to simulate the entire textile weaving process. It employs the DEA to simulate weaving actions, boundary conditions, inter-fibre forces (contact and friction), and fibre forces (tensile, bending, shear, and damping). The work presented in this paper is organised as follows: (1) the necessary components of a Jacquard loom to perform all weaving functions are explicitly modelled and illustrated; (2) the mechanisms of all principal weaving actions, especially the relation between yarn interlacing motion and fabric pattern, are explained; (3) the weft yarn tension and periodic
boundary conditions in the warp direction are established; and (4) the weaving process of a 3D orthogonal woven fabric is simulated step by step and compared to micrographs of an actual fabric. The changes in cell width, thickness, and fabric microstructure during weaving are closely monitored, followed by a parametric study on the effects of yarn tension and take-up length on fabric thickness and reed tension.

**Dynamic weaving simulator**

**Weaving machine**

Weaving is the interlacing of two or more sets of threads: a lengthwise warp thread and a crosswise weft thread. The Jacquard loom is a specialised loom based on a system of punch cards and hooks with which a weaver can produce complicated and intricate patterns. Figure 1 schematically illustrates the simulated loom based on the Jacquard principle. The purple and green strips are warp and binder yarns, respectively, and the yellow strips are weft yarns. The key machine components are shuttles, reeds, heddles, harnesses, take-up rolls, and tension devices, which actuate the basic operations of the weaving cycle.

Harnesses are cords arranged vertically, with the upper ends connected to lifting units and the lower ends attached to springs. Heddles are carrier devices for warp and binder yarns. One heddle corresponds to one harness cord, and each heddle contains an eye through which the warp or binder yarn can pass. The harness cords move vertically during

![Figure 1. Schematic diagram of the simulated weaving machine.](image)
weaving and change the up/down positions of the attached heddles. The heddle positions control the weaving motion and determine the interlacing pattern of the fabric.

Jacquard Loom is controlled by a chain of multiple cards punched with holes that determine which cords of the fabric warp should be raised for each pass of the shuttle. Similar to Charles Babbage and Ada Lovelace’s ‘analytical engine’, this model utilizes a ‘hole/no hole’ principle with the numbers ‘1’ and ‘−1’ to convey data or information related to weaver movements. The number of harnesses, which correlates to the spacing of the heddles and reeds, can be adjusted to achieve a user-defined fabric width.

Weaving actions

The weaving cycle primarily consists of shedding, weft insertion, beat-up, and take-up motions. Multiple weaving cycles are required to produce a fabric.

**Shedding and weft insertion:** During each weaving step, heddles lift or lower the connected warp or binder yarn to form a space between the fell and heddle for shuttle motion. The shuttle then moves across the encircled space and lays one weft yarn. In the proposed model, the weft package is separated from the shuttle for high-speed weft insertion by implementing a shuttle-less feature. Weft cones or packages are directly used as the weft supply, and the weft insertion mechanism uses a weft accumulator so that fibre loss during weft insertion can be neglected.

An analytical engine was built into the model to substitute the punch card system that carries instructions for guiding the inserted weft yarns to the right locations with a digital matrix. The basic concept of this engine is simple, without the need for heavy mathematical calculations. Take, for example, the 3D woven fabric in Figure 1. It consists of four warp yarns (in green) and four binder yarns (in purple). As shown in Figure 2(a), each of them is assigned a consecutive number. As illustrated schematically in Figure 2(a)–(f), a minimum of six steps is required to complete a weaving cycle. During each step, one weft yarn is inserted by the shuttle, and the position of the warp and binder yarns are interchanged according to the weaving matrix in Table 1, which includes the minimum number of steps of a weaving cycle, and the harness position for each warp and binder yarn at each step. When the value in the matrix equals ‘1’, the harness is in the ‘up’ position, whereas ‘−1’ sets the harness in the ‘down’ position. By repeating steps (a)–(f), the simulated loom produces the patterned fabric that the weaving matrix has instructed it to create.

**Beat-up:** The beat-up action follows weft insertion. The main function of the beat-up mechanism is the reciprocating motion of the reed. During weaving, the reed, which precisely determines the warp density and fabric width, holds the warp ends at a given distance. It then guides the weft carrier across the warp sheet and beats the inserted weft thread into the fabric fell against the preceding wefts. In the proposed model, the reed was modelled as a rigid cylindrical bar parallel to the z-axis and moved in the x-direction. For a distance $S_r$ between the initial reed position and fell and beat-up time $T$, the reed acceleration is expressed as
The reed must be returning towards the back of the loom before the shed is large enough to admit the weft package. This determines the timing of the picking motion, which is related to the positions of the reed and sley. Note that the sley is not directly modelled in the proposed model but is represented by reed distance and speed.

\begin{equation}
 a_r = \frac{2S_r}{T^2}
\end{equation}

Figure 2. Schematic diagram of a 3D woven fabric weaving process in correspondence with the weaving matrix in Table 1.

Table 1. Weaving matrix.

| Step # | Yarn # | Binder yarn | Warp yarn |
|--------|--------|-------------|-----------|
|        |        | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1      |        | 1 | 1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 2      |        | 1 | 1 | 1 | 1 | -1 | -1 | -1 | -1 |
| 3      |        | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4      |        | -1 | -1 | -1 | -1 | -1 | -1 | 1 | 1 |
| 5      |        | -1 | -1 | 1 | 1 | -1 | -1 | 1 | 1 |
| 6      |        | -1 | -1 | 1 | 1 | 1 | 1 | 1 | 1 |

Harness position: one means up; -1 means down.
Take-up: The take-up motion determines the number of wefts per centimetre width and contributes to the uniform texture of the fabric. Thus, the fabric unit cell width determines the take-up speed. In the proposed model, the woven fabric is shifted left with respect to the fell at a constant speed to mimic the roller motion. A take-up flag, with reference to the number of weft rows, is employed to control the take-up rate. That is to say, the take-up action takes place after every certain number of weft yarns are inserted.

By repeating the aforementioned weaving actions, a continuous weaving process is simulated.

**Forces and boundary conditions**

The fibre tensile force, inter-fibre contact force, frictional force, damping force, and shear force have been considered and presented in previous studies. In this section, we discuss the weft yarn tension and periodic boundary conditions.

**Weft yarn tension:** A cross-sectional view of the weaver yarns is shown in Figure 3(a), illustrating the formation of weft yarn tension during interlacing. This model includes four stages. In stage I, a weft yarn is inserted at the fell; it is assumed to be straight and without tension. Then, the warp and binder yarns in the up and down positions move towards the weft yarn in opposite directions. They contact the weft yarn in stage II and continue moving in the same direction through to stage IV. Both warp/binder and weft yarns start to deform in stages III and only static friction has developed between them. When the contact force between the warp/binder and weft yarns is larger than the frictional force, the warp/binder yarns start to slide along the weft yarn, entering stage IV.

A segment of a digital fibre consisting of rod elements \((i-1, i)\) and \((i, i+1)\) is connected by a torsional spring \(i\), as shown in Figure 3(b). The weaving-induced contact force \(F\) denoted by the red arrow acts in the same direction as the warp and binder yarn motions. Assuming that the components of \(F\) perpendicular to and along the weft yarn...
path are $F_{per}$ and $F_{alo}$, respectively, the frictional force between the weft and warp/binder yarns is $f$. When equation (2) is true, the weft and warp/binder yarns are subjected to sliding. Where $f_S$ is the maximum static frictional force between the weft and warp/binder yarns and $\mu$ is the friction coefficient.

Sticking and sliding cause the weft yarns to “buckle” and change the element length; therefore, the inserted weft yarn length should be equal to or greater than the nominal width of the fabric. A buckling coefficient $\delta$ is introduced to control the weft yarn length. As shown in Figure 3(c), the tension induced nodal force $\vec{F}_i$ applied to node $i$ is calculated as

$$\vec{F}_{(i-1,i)} = E A \frac{l_{(i-1,i)}}{l_0} - \delta l_0$$  \hspace{1cm} (3)$$

$$\vec{F}_{(i,i+1)} = E A \frac{l_{(i,i+1)}}{l_0} - \delta l_0$$  \hspace{1cm} (4)$$

$$\vec{F}_i = \vec{F}_{(i-1,i)} + \vec{F}_{(i,i+1)}$$  \hspace{1cm} (5)$$

where $\vec{F}_{(i-1,i)}$ and $\vec{F}_{(i,i+1)}$ are the tension-induced forces of rod elements $(i - 1, i)$ and $(i, i + 1)$, respectively; $E$ is the fibre longitudinal modulus; $A$ is the fibre cross-sectional area; $l_{(i-1,i)}$ and $l_{(i,i+1)}$ are the deformed element lengths of rod elements $(i - 1, i)$ and $(i, i + 1)$, respectively; and $l_0$ is the original element length, it equals to the nominal width of the fabric divided by the total number of elements.

When the deformed element length $l$ is bigger than $\delta l_0$, tension develops.

**Periodic boundary condition:** During the fabric manufacturing process, a boundary effect exists near the edges and demonstrates properties different from that of the remaining fabric piece. Hence, a periodic boundary condition similar to that utilised in the dynamic relaxation approach was implemented only in the weft direction. As shown in Figure 4, the simulation domain includes a primary region (in green) and two image regions (in grey). $A$ and $B$ are internal boundaries, whereas $A'$ and $B'$ denote external boundaries. The widths of both the internal and external boundaries are the same and are denoted as the mapping width.
In each simulation step, nodal forces, accelerations, velocities, and displacements in the internal boundaries were calculated and mapped to the external boundaries based on the periodic principle. Then, the nodal positions in the image regions were used to calculate the forces in the boundary vicinity of the primary region.

In this approach, a central-difference explicit numerical algorithm is utilised to calculate nodal accelerations, nodal velocities and nodal displacements. 80–90% of computing time is used to search and calculate contacts between fibres, hence, the total number of nodes and the time step controls the calculation efficiency. To avoid penetration between fibres and achieve maximum calculation efficiency, it is recommended that the length of the digital rod element is equal to the digital fibre radius and the time step equals to half of the critical time step of the digital filament. Besides, excessive yarn tension could also leads to fibre penetration.

**Weaving simulation**

**Weaving pattern and fibre property**

The fabric under investigation was made of Nicalon CG fibres and manufactured by Materials Research & Design, Inc. (MR&D). Figure 5 illustrates the unit cell topology. The weft yarns were numbered 1–40, which is consistent with the weft insertion order. The binder and warp yarns were numbered 1’–11’, and their interlacing motions correspond to the weaving matrix in Table A1 of Appendix A. The weft yarns were arranged in ten layers and two columns, with one warp yarn between each layer and two weft yarns in each column. Binder yarns move all the way under and over the weft yarns and provide strength to the structure.

![Figure 5. Unit-cell topology.](image)
The material properties of the Nicalon CG fibres and the weaving parameters used in the simulation are listed in Tables 2 and 3, respectively. Tension inside the warp and binder yarn filaments is set to be 0.16 N and 0.02 N, respectively. For the weight and length measurements, 5–10 yarn segments were taken from the as-received fabric and weighed using an analytical balance at the Kansas State University Composites Laboratory. The denier number and cross-sectional area derived from the measured yarn weight and length were both approximately 10% higher than those specified in the datasheet. Hence, the actual measurements were adopted in the simulation. The weaving parameters were designed according to the fabric pattern and unit cell dimensions based on the Jacquard mechanism.

**Comparison**

The simulation is carried out on PC and takes approximately 72 h to finish. The model of processor and RAM for this computer is Intel(R) Core(TM) i7-9700 CPU @ 3.00 GHz, 16 GB. Front- and top-view images of the simulated fabric at five different stages are shown in Figure 6. Notably, the microstructure of each cell continued to change after being woven. As the number of weaving steps increased, the cell width and thickness both decreased in oscillation. Take cell two as an example. In step 80, the right edge of the weft yarns was lined up with the reed at the fell, leaving an empty triangular region encircled by binder yarns. After weaving cell three (step 120), the empty space had disappeared and was filled with filaments, causing a reduction in the cell thickness and width. The microstructure of cell two ceases to change at approximately step 160 or beyond. These findings dynamically and thoroughly illustrate the formation process of a single cell in a woven fabric.

The changes in cell length and thickness were recorded and are quantitatively shown in Figure 7 (Refer to Table A3 in Appendix A for more detail). As shown, length and thickness of all cells decreased and converged as the weaving steps increased. The cell width and length is controlled by the weaving parameters shown in Table 3 and set to be the same as that of the experimental ones. Hence are not discussed here. The thickness of cell two, cell three, and cell four is 3.46 mm, 3.27 mm, and 3.17 mm at step 200, respectively, which is 3.62%, 8.86%, and 11.62% lower than the measured fabric thickness. It shows that the dimension of cell two is the closet to the fabric specimen.

The simulated fabric was assembled in the weft direction, and the microgeometry of cell two was investigated. As shown in Figure 8, the fabric cross-sections at four different locations were obtained and compared with microscopy images of the actual fabric.

### Table 2. Material properties of nicalon CG.

| Denier (g/9000 m) | Fibre density (kg/m³) | Yarn cross-sectional area (m²) | $E_{11}$ (GPa) | $E_{22}$ (GPa) | Friction coefficient $\mu$ |
|------------------|----------------------|-----------------------------|-------------|-------------|------------------------|
| 1987             | 2550                 | $8.66 \times 10^{-8}$       | 190         | 19          | 0.2                    |


Table 3. Weaving parameters.

| Weaving parameters                  |               |
|-------------------------------------|---------------|
| Loom  | Length (m) | 0.006         |
|       | Height (m) | 0.0028        |
| Reed   | Section    | 3             |
|        | Width (m)  | 0.00053       |
|        | Distance (m) | 0.0058     |
|        | Diameter (m) | 0.00014   |
| No. of digital fibres per weft/warp/binder yarn | 19/19/19 |
| Take-up flag (/row)                    | 10            |
| Buckling coefficient                    | 1             |
| Mapping width (m)                      | 0.00053       |

| Fabric pattern and topology dimension |               |
|-------------------------------------|---------------|
| Weft row                            | 10            |
| Weft column                          | 4             |
| Warp section                         | 3             |
| Cell dimension                       |               |
| Length (m)                           | 0.00508       |
| Width (m)                            | 0.00159       |

Figure 8(a) shows the fabric piece in isometric view and illustrates the Section location. Sections 2 and 4 are perpendicular to the weft yarns. Section 2 is in between the binder yarns, whereas Section 4 cuts through the binder yarns. Similarly, Sections 1 and 3 are perpendicular to the warp yarns. Section 1 cuts through the weft yarns, whereas Section 3 is in between the weft yarns.

Comparing Section 2–4 and Section 1–3 shows that the fabric, as well as the yarn cross-section varies at different location of the same direction. As shown in Figure 8(c), the weft yarn path on top and bottom are close to a sinusoid shape due to binding force, while the ones in the middle are almost straight. Evidence of stress concentration can also be observed from the cross-sectional shape of the weft yarns. Considering that the fabric microstructure varies by cell and cross-section, it is therefore safe to conclude that the simulated fabric is in general agreement with the actual specimen.

Figure 9 compress the cross-sectional areas of the weft yarns in Sections 2 and 4 to those in the microscopy image. (Refer to Table A2 in Appendix A for more detail). The weft yarns were numbered from top to bottom. As shown, the variation in weft yarn cross-sectional area has a normal distribution and is consistent with that in the microscopy image. The cross-sectional area of each individual weft yarn in Section 2 was generally larger than that in Section 4. These results show that the binding force reduces the space between the filaments and leads to a compact arrangement. The weft yarns at the top and bottom of the cell were more closely packed than those in the centre. These observations demonstrate the challenges in predicting yarn material properties.
Figure 6. Front and top view of the simulated fabric at five different stages. (a) Stage 1: total of one cell (step 40). (b) Stage 2: total of two cells (step 80). (c) Stage 3: total of three cells (step 120). (d) Stage 4: total of four cells (step 160). (e) Stage 5: total of five cells (step 200).
Weaving process analysis

The simulation of weaving the first cell, corresponding to the 40 weaving steps listed in Table A3 of Appendix A, is shown schematically in Figure 10. All yarns were discretised into 19 filaments. The binder and warp yarns were fixed at the left end.

Figure 7. Change of cell width and thickness versus weaving steps. (a) Unit-cell width. (b) Unit-cell thickness.

Figure 8. Comparison between microscopy images and simulated fabric. (a) Isometric view of the fabric and the illustration of the Section location of (c), and (d), (b) Fabric microscope images, (c) Section 1 and 2, (d) Section 3 and 4.
whereas the weft yarns were free from constraints. In each step, one weft yarn was inserted at the initial reed position. Then, the inserted yarn was beat by the reed towards the woven fabric at constant acceleration until reaching the fell, where it contacted the binder and warp yarns. Yarn interlacing took place every other second steps. The warp and binder yarns wrapped over the weft yarns, causing their cross sections to deform into various shapes. The inter-filament movement and fabric microstructural evolution were demonstrated in detail.

A close-up isometric view of the weft insertion and shedding motions is shown in Figure 11, demonstrating the dynamic change in the yarn microgeometry during weaving. Close attention was paid to the weft yarns in the second row, encircled by a dotted white line. The reed, which causes the kinks in binder yarns near the fell, is removed from the display for ease of viewing. In Step 141, one binder yarn is in the ‘up’ position and all warp yarns are in the ‘down’ position, and the weft yarns encircled by a dotted white line are constrained by adjacent warp yarns and tightly packed in a racetrack cross-sectional shape. In Step 142, the binder yarn on top is lifted by the harness, creating a V-shaped passage at the fell, which is much larger than the yarn cross-sectional area. Consequently, the filaments in the weft yarns in the second row (encircled by the white dotted line) were scattered to random locations, which completely transformed the cross-sectional shape of the yarns. In Step 144, when two consecutive weft yarns were pushed to the fell, the binder yarn on top of the remaining yarns was lifted and pressed against the weft yarns in the second row by the harness, forcing them to deform back into a racetrack shape. Thus, the microstructural evolution of weft yarns in the shed was confirmed and observed numerically for the first time. Notably, the filaments in the encircled yarns were massively disrupted by the beating motion at Step 143, with inter-yarn penetration during the interlacing motion. This demonstrates that the microstructure, composition, and material properties of the weft yarns are inherently changed during the weaving process and can only be modelled accurately at the sub-yarn scale.
Parametric study

Effects of yarn tension on fabric structure and reed tension: Simulations were performed with five different combinations of warp and binder yarn tensions to investigate the effect of yarn tension on reed tension, fabric thickness, and crimp angle. The results are summarised quantitatively and qualitatively in Table 4 and Figure 12. As shown in Table 4, the fabric geometry of set one was closest to that of the actual specimen. The
binder and warp yarn tensions are inversely and directly proportional, respectively, to both the thickness and crimp angle. As shown in Figure 12, the reed tension spikes periodically every 20 steps during shedding formation, with a magnitude of approximately 5–10 times the average reed tension. This phenomenon is in general agreement with Bessette’s experimental findings reported in.33 Comparing sets one to three shows that increasing the binder yarn tension leads to an increase in reed tension, which is consistent with Kim’s work presented in.34 However, changing the warp yarn tension had no effect on reed tension. When the binder yarn tension was doubled, the fabric thickness decreased by 25%. Similarly, when the warp yarn tension was doubled (comparing sets five to one), the fabric thickness increased by 22%. These findings are in general agreement with Nasan’s experimental work reported in.35 Comparing sets three to five shows that when the warp and binder yarn tensions are doubled simultaneously, the fabric thickness decreases by only 3.5%, indicating that the fabric thickness mostly depends on the tension ratio between the warp and binder yarns. Considering that the binder yarn tension is 4–8 times smaller than the warp yarn tension, the former plays a slightly more significant role in determining the fabric structure.

Figure 11. Close-up isometric view of weft insertion and shedding at (a) Step 141 (b) Step 142 (c) Step 143 (d) Step 144.
Effects of take-up length on fabric structure and reed tension: Take-up actions were conducted twice in every 40 steps during weaving. To investigate the effect of take-up length on the fabric microgeometry and reed tension, simulations were conducted with take-up lengths of 5.08, 6.35, and 7.62 mm. As shown in Figure 13, the take-up length directly affects the fabric width and thickness. In addition, increasing the take-up length

Table 4. Comparison of simulated fabrics with different yarn tension combinations.

| Set # | Warp (N) | Binder (N) | Ratio | Thickness (m) | Discrepancy (%) | Crimp yarn angle (°) | Discrepancy (%) |
|-------|----------|------------|-------|---------------|------------------|----------------------|----------------|
| 1     | 0.16     | 0.02       | 8.0   | 0.00364       | 1.39             | 79                   | 1.29           |
| 2     | 0.16     | 0.03       | 5.3   | 0.00307       | 14.48            | 77                   | 1.57           |
| 3     | 0.16     | 0.04       | 4.0   | 0.00273       | 23.96            | 71                   | 9.24           |
| 4     | 0.12     | 0.02       | 6.0   | 0.00330       | 8.08             | 78                   | 0.29           |
| 5     | 0.08     | 0.02       | 4.0   | 0.00283       | 21.17            | 75                   | 4.13           |

Note: The thickness and crimp angle of the actual specimen were 0.00359 m and 78.23°, respectively.

Figure 12. Effect of yarn tension on reed tension. (a) Effect of binder yarn tension on reed tension. (b) Effect of warp yarn tension on reed tension.
allows more weft filaments to shift in the warp direction and mix with neighbouring weft yarns. As shown in Figure 14, as the take-up length and number of weaving steps increases, the peak reed tension generally decreases. However, the reed tension between interlacing yarns remains almost the same.

**Conclusion**

The weaving process of a 3D orthogonal woven fabric was simulated step-by-step at the filament level by using the proposed method to derive and investigate the microstructural evolution that occurs during weaving. The simulation results were compared with microscopy images of an actual specimen. The following conclusions were drawn.

1. The weaving process of the 10 layers 3D orthogonal woven fabric was successfully modelled step-by-step at the filament level. Five cells in the warp direction were produced. The simulation findings reveal that the fabric microstructure continues to change after being woven. The width and thickness of a single cell decrease with an increase in the number of weaving steps.

2. It takes approximately 80 steps (the number of steps to produce two cells in the lengthwise direction in this case) for the microstructure of a newly woven cell to converge. The cross sections of the second cell in the weft and warp directions closely match the microscopy images.
3. The microstructure of the weft yarns next to the fell changes drastically during the shedding motion. When some of the warp yarns are raised and the rest are lowered, the fabric next to the fell rips open between the warp yarns in the ‘up’ and ‘down’ positions. A V-shaped passage much larger than the yarn cross-sectional area was formed, causing filaments inside the passage to scatter in random directions in an extremely loose state. These filaments were disrupted again by the beating motion before deforming back into a racetrack cross-sectional shape.

4. Penetration of weft yarns in the same column occurs during the interlacing motion. When two weft yarns are pushed to the fell consecutively, their filaments are massively disrupted and mix together by the beating up and during interlacing motion. As a result, the yarn microstructure and composition change during weaving, which alters the material properties such as, density, transverse modulus, bending stiffness, etc.

5. The proposed approach is validated by comparing the simulated fabric cross-sections to the microscopy images. The variation in weft yarn cross-sectional area has a normal distribution with the ones at the top and bottom of the cell were more closely packed than those in the centre.

6. Increasing the binder yarn tension decreases fabric thickness, whereas increasing the warp yarn tension or take-up length reduces fabric thickness. When the ratio between the warp and binder yarn tensions was the same, the fabric thickness remained the same. Reed tension is directly and inversely proportional to binder yarn tension and take-up length, but insensitive to warp yarn tension.

Author contributions
Ying Ma: Conceptualization, Methodology, Software. Weihong Xiang: Data curation, Writing Original draft preparation. Sheng Lu: Visualization, Resources, Supervision. Hanjie Hu: Funding acquisition. Xianjun Zeng: Writing-Review & Editing.

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Supplemental Material

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