An efficient virtual modeling regard to the axial tensile and transverse compressive behaviors of the twisted yarns

Yu Wang\textsuperscript{1,2,3}, Yanan Jiao\textsuperscript{1,2}, Ning Wu\textsuperscript{1,2}, Junbo Xie\textsuperscript{1,2}, Li Chen\textsuperscript{1,2} and Peng Wang\textsuperscript{3}

Abstract
The mechanical properties of yarns have a decisive effect on the performance of fiber-reinforced composite materials. Predictive simulations of the mechanical response of yarns are, thus, necessary for damage evaluation and geometric reconstruction of textiles. This paper proposed a quasi-fiber scale virtual modeling method regard to the axial tensile and transverse compressive behaviors of the twisted yarns. A stochastic properties model of the yarn was established for characterizing the statistical distribution of tensile strength. The variation of modeling parameters, including coefficient of friction, the amounts of virtual fibers per yarn and element length, versus calculation accuracy has been determined based on axial tensile and transverse compressive behavior of quartz fibers. The relationship between modeling parameters and mechanical behavior of yarn was established within the scope of this study. Axial tensile and transverse compressive behavior of yarns with different twists were predicted. The results show that balance between the modeling precision and computational efficiency can be achieved using the

\begin{flushleft}
\textsuperscript{1}Ministry of Education Key Laboratory of Advanced Textile Composite Materials, Institute of Composite Materials, Tiangong University, Tianjin, China
\textsuperscript{2}School of Textile Science and Engineering, Tiangong University, Tianjin, China
\textsuperscript{3}Laboratoire de Physique et M\'ecanique Textiles (LPMT), \'Ecole Nationale Sup\'erieure d'Ing\'enieurs Sud-Alsace (Ensisa), Universit\'e de Haute-Alsace, Mulhouse, France
\end{flushleft}

Corresponding author:
Junbo Xie, Tiangong University, No.399 Bin-Shui West Road, Xi-Qing District, Tianjin 300387, China.
Email: xiejunbo@tiangong.edu.cn

Creative Commons Non Commercial CC BY-NC: This article is distributed under the terms of the Creative Commons Attribution-NonCommercial 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/) which permits non-commercial use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
parameters, the COF of 0.35, virtual fiber count of 122 and Le of 0.3. This efficient modeling method is meaningful to be developed in further virtual weaving research.

**Keywords**
Virtual fiber, numerical simulation, quasi-fiber scale modeling, yarn damage, axial tensile behavior, transverse compressive behavior

**Introduction**
Fiber-reinforced composites have been widely used in aerospace, aviation, maritime, biomedicine, and infrastructure, due to their excellent mechanical properties, structural desig-nability and fatigue resistance.\(^1\text{-}^3\) The study of mechanical properties of fiber-reinforced composites has become a hot topic.\(^3\text{-}^5\) As a vital part of fiber-reinforced composites, the mechanical behavior of the yarn will significantly disperse the mechanical properties of the composite, such as tensile, compression and bending.\(^6\text{-}^8\) Therefore, some methods for the evaluation of yarns performance are needed to develop fiber-reinforced composites with higher specific strength and specific modulus. Lamon et al.\(^9\) investigated the flaw strength distributions of various fiber types and constructed empirical distributions of flaw strength that allow the evaluation of Weibull plot and Maximum Likelihood Estimation methods as functions of sample size and composition. Wang et al.\(^10\) proposed an analytical model based on statistic theory to demonstrate the stochastic tensile properties of natural fiber yarns by defining crimp strain of fibers and effective elastic modulus of yarns as stochastic variable of damage indicator. A simple mechanical approach to reproduce the evolutions of width and thickness of E-glass and carbon tows during through-thickness compaction was experimentally proposed by Hemmer et al.\(^11\) The above scholars established an analytical model applied to fiber/yarn combined with the experimental conclusions.\(^12\text{-}^14\) In addition, the structure of the yarn changes during its stretching and compression. Hence, understanding and predicting the tensile and compressive behavior of yarns is crucial step for composite molding research.\(^15,16\)

Based on an advance in yarn material analytical model above, a numerical simulation model based on the analytical model was gradually established. Generally, existing numerical simulation models are established by digital element, truss element and beam element.\(^17\) Zhou et al.\(^18\) extended a digital element approach (DEA) (developed by Wang et al.\(^19\) in 2001) to fiber-level, named multi-chain digital element method. In this model, each yarn was defined as an assembly of fibers and each fiber is represented as a digital chain. Daelemans et al.\(^20\) developed a yarn model with truss element, which can predict the mechanical response of the fabric by considering the sub-yarn behavior without the requirement for complex constitutive laws. Moustaghfir et al.\(^21\) used a finite strain beam model to represent each fiber of the roving, focusing on studying the influence of the roving twist, tensile force and friction coefficient on the compressive behavior. These three modeling methods allow for simulation analysis and prediction. Nevertheless, the bending moments are not available in the digital element and truss elements. The beam elements with bending stiffness can realize the simulation analysis in which the contact
interaction and squeezing deformation of the yarns cannot be considered under complex mechanical behavior.

To acquire a more accurate model, the internal geometry of the model was compared with Micro-CT images. Xie et al.\textsuperscript{22,23} proposed a numerical simulation of the weaving process for understanding the fiber architectures of textile composites and used Micro-CT technology to validate the accuracy of the virtual fiber structure. Few studies have focused on the mechanical behavior of yarns by numerical simulation method, except for amounts of research that established the mechanical relationship between yarn and fabric. Daelemans et al.\textsuperscript{20} described a solution that enables predict compression simulations through hybrid virtual fibers, the compression of a woven fabric ply is simulated and experimentally validated by the Micro-CT. The high precision models of yarns can be generated using the above methods. However, a more realistic yarn model needs to take into account the damaged properties. In the previous work of Xie,\textsuperscript{24,25} the virtual fiber modeling method was used to simulate the needling process of a quartz fabric layer, where fiber deformation and damage were involved. However, the mechanisms of damage and deformation of yarns which highly depend on several fiber-level interactions which are related to $COF$ (coefficient of friction), especially twisted yarns, have not been adequately explained.

In present study, the yarns were modeled by a flexible chain consisting of beam elements (B31 elements in Abaqus software) based on Micro-CT reconstruction results. A constitutive model with stochastic damage properties was applied according to the Weibull distribution. The axial tensile and transverse compressive behavior of the yarns were then simulated by applying appropriate displacement boundary conditions on the end of the yarns in explicit solver Abaqus\textregistered Explicit, meanwhile, the coefficient of friction, amounts of virtual fibers per yarn and element length were considered. An image analysis method was used to validate the accuracy of the yarns model. Indeed, the geometric deformation and mechanical behavior of yarns with different twists were predicted under specified boundary conditions. This modeling method provides a helpful tool for understanding the mechanical response of yarns.

**Material and Experiments**

**Material**

Four groups of yarn samples were prepared and tested under tensile and compressive loads. Detailed parameters of the samples are listed in Table 1. All the yarns are composed of B-type quartz fibers and supplied by Feilihua Quartz Glass Co., Ltd (Hubei Province, China). When referring to a sample, the labels $P$ and $T$ represent ply number and twist level of yarns, respectively. For example, P2-T150 means that the sample is composed of double-ply yarns and the twist level of each single-ply yarn is 150 tpm (twist per meter). All the double-ply yarns were prepared by twisting two single-ply yarns, each of them having a twist of 80 tpm. The volume density and diameter of the B-type quartz single twisted yarn are 2.2 g/cm$^3$ and 7.5 μm, respectively.
Tensile and compressive tests

Tensile tests of yarn samples were carried out according to ISO 2062 (1993) standard on SHIMADZU (AGS-J 1 kN) test machine, as shown in Figure 1. The gauge length of the samples was 500 mm. The sample applied a pre-tension force of 30.0 ± 1.5 mN/tex and the loading rate was 200 mm/min. The compressive tests were conducted on a Bruker UMT TriboLab machine equipped with a 100 N load sensor. The yarn sample was subjected to compressive load between two platens (with the size of 50 × 30 mm$^2$) at the rate of 1 mm/min. Twenty samples were tested in each group, during the tensile/compressive load and deformation were recorded.

The Micro-CT observation

The Micro-CT technology was employed to observe the deformation of the yarns during the compression, as shown in Figure 2. A P2-T150 compressed sample with a length of 50 mm was scanned by an X-ray CT test (Xradia-510 versa, Zeiss). The X-ray source emitted a cone-beam which passed through the sample and was then absorbed by the receiver platen. The radiographs were acquired with a voxel size of 5 μm, beam energy of 50 kV and a current of 80 μA. A total of 1130 projections were acquired and then stitched for the image reconstruction. The reconstructed images were imported into Dragonfly.

| Samples | Linear density (Tex) | Twist level (tpm) | Direction of twist | Modulus (GPa) |
|---------|----------------------|-------------------|-------------------|--------------|
| P1-T80  | 1×190                | 80                | S                 | 72.7 (±5.5)  |
| P2-T80  | 2×190                | 80                | SSZ               | 65.7 (±6.5)  |
| P2-T150 | 2×190                | 150               | SSZ               | 65.5 (±4.5)  |
| P2-T200 | 2×190                | 200               | SSZ               | 63.7 (±1.5)  |

Figure 1. Mechanical tests of yarn samples: (a) Axial tensile test and (b) transverse compressive test with pre-tension.
software (version 2020.1, Object Research Systems (ORS) Inc.) for segmentation, 3D visualization, and quantitative analysis.

Image processing methods were utilized to observe internal details of yarn, whose key are about parameters adjustment of images. The grayscale value refers to the brightness of a single pixel, which can clarify the volume of interest. The estimated grayscale threshold was set at the beginning of reconstructed image processing to extract the volume of interest from the whole volume, which contained a gray value distribution of the air (voids), platens, and yarn. The accurate grayscale threshold (35,209–57,825) was obtained from the whole volume (0–65,535) using the histogram tool in the Dragonfly software.3,4

Virtual fiber and virtual yarns modeling

Geometry and property models

The geometric of yarns are determined by fiber arrangement at the quasi-fiber scale.21,26 In this paper, the virtual yarn was used to model the mechanical behavior of the realistic yarn. The virtual fiber is modeled by a chain of beam elements in the Abaqus software. A certain number of virtual fibers with twist angle is assembled to form a twisted yarn using the Python script and running on the Dell workstation (Precision 7820 Tower) by the following equation. As shown in Figure 3(a), large number of beam elements constitute a virtual fiber. The equations (1) and (2) reflect the constraint relationship between beam nodes.

\[
\theta_0 = \pi - n \times \arcsin \left( \frac{z_0}{r_{\text{point}}} \right) \quad (1)
\]

\[
\begin{align*}
x' &= x_0 + \kappa \times L_e \\
y' &= r_{\text{point}} \times \cos (\theta_0 + \kappa \theta_t) \\
z' &= r_{\text{point}} \times \sin (\theta_0 + \kappa \theta_t)
\end{align*}
\] 

Figure 2. The micro-CT test of yarn sample under compression: (a) compression test, (b) yarn sample with platens and (c) Micro-CT test.
where, $x'$, $y'$ and $z'$ are coordinates along $x$, $y$ and $z$ directions, separately. $\kappa$ is the number of the element. $r_{\text{point}} = \sqrt{x_{0}^{2} + y_{0}^{2}}$ is the distance between the node and the center of the circle on the section. $\theta_t$ and $\theta_0$ are the twist of yarns and deflection angle of the element, which is normalized by $n$. Furthermore, the number of fibers can be obtained by equation (3).

$$\pi \times \left( \frac{D_f}{2} \right)^2 \times n_f = \frac{\rho_f}{\phi_f}$$

where, $n_f$ and $D_f$ are the amount and diameter of virtual fibers in the yarn, $\phi_f$ and $\rho_f$ are volume density and linear density of realistic yarn.

Towards exploring a more accurate mechanical response of yarn, the properties with Weibull distribution need to be assigned to each virtual fiber based on the stochastic distribution algorithm. The factors with Weibull distribution of fibers -scale and shape factor-are obtained from research, probability of fiber can be obtained by equation (4).

$$P_f(\sigma) = 1 - \exp \left[ - \left( \frac{\sigma}{\sigma_0} \right)^m \right] = \frac{i}{N_f + 1}$$

where $m = 5.50$ is the Weibull modulus or shape factor, $\sigma = 3810$ MPa is the obtained stress, $\sigma_0$ is the characteristic strength or scale factor. $N_f = 74$ is the number of tests, $i$ is the test serial number (ranked). According to the above method, numerous factors $\sigma_0$ are applied to assign material properties of each virtual fiber. Meanwhile, the same materials property (Effective elastic modulus $E = 68$ GPa and Poisson’s ratio $\nu = 0.01$) are also assigned to each virtual fiber.

**Damage model**

Based on previous research, the fiber and yarn are considered to be transversely isotropic homogeneous materials, and the damage model of the fiber is the same as that of the yarn. Initially, the yarn damage is considered to be elastic due to no significant plastic deformation. Once the ultimate strength is reached, the progression of damage is
characterized by material stiffness degradation. The damage process may be explained using the damage variables as internal variables. Herein, we use the Matzenmiller damage tensor and continuum damage mechanics (CDM) theory to calculate the stiffness degradation for yarn. The expressions of the damaged and undamaged constitutive relations for yarn are as follows

$$u_f = S_f(d_f) \cdot F_f = S_{f0}^{-1} : u_f$$

(5)

where $F_f$ and $u_f$ are the load and displacement of yarn, and the $S_f(d_f)$ is damaged compliance matrix

$$S_f(d_f) = \begin{bmatrix}
1 & 1 & 1 \\
(1 - d_{f,1}) \sum_j E_{f,1} A_j & \sum_j z_j E_{f,1} A_j & \sum_j y_j E_{f,1} A_j \\
\sum_j z_j E_{f,2} A_j & \sum_j z_j^2 E_{f,2} A_j & \sum_j y_j z_j E_{f,2} A_j \\
\sum_j y_j E_{f,3} A_j & \sum_j y_j z_j E_{f,3} A_j & \sum_j y_j^2 E_{f,3} A_j
\end{bmatrix}$$

(6)

where the subscripts 1, 2 and 3 represent the longitudinal direction of the yarn and two transverse directions, respectively. The subscripts $j$ is label of each fiber on a cross-section. The $A_j$ is the integration weight of the coordinates, which is the area corresponding to the fibers in general. The elastic constants of the fiber are provided by the manufacturer. $S_f(0)$ is the compliance matrix without damage which is obtained from equation (6) when the values of damage variable is zero. In the damaged compliance matrix, the damage variable $d_{f,1}$ represents the fiber axial brittle fracture.

The damage initiation criteria for yarns are respectively formulated as

$$F_{f,N} = \phi_{f,N} - r_{f,N} \leq 0, N = \{1t, 1c, 2t, 2c, 3t, 3c\}$$

(7)

where $t$ and $c$ denote tension and compression. $\phi_{f,N}$ indicate the loading function of yarn. $r_{f,N}$ is the damage threshold.

The exponential damage degradation model (Figure 4(a)) is adopted. A linear and exponential damage evolution model (Figure 4(b)) is utilized for the longitudinal stretching of yarns. The damage factors of yarns can be expressed as

$$d_{f,1t} = 1 - \frac{1 - d^e_{f,1t}}{r^e_{f,1t}} \exp[A_{f,1t}(1 - r^e_{f,1t})]$$

(8)

$$d_{f,N} = 1 - \frac{1}{r_{f,N}} \exp[A_{f,N}(1 - r_{f,N})], N = \{1c, 2t, 2c, 3t, 3c\}$$

(9)
here $A_{f,N}$ is damage degradation parameter. $r_{f,1t}^e$ and $d_{f,1t}^l$ are the auxiliary damage threshold and auxiliary variable of yarns, respectively

$$d_{f,1t}^l = 1 + \frac{K_{f,1} E_{f,1}}{r_{f,1t}^l} \left( 1 + \frac{K_{f,1}}{E_{f,1}} \right) \frac{1}{r_{f,1t}^l} \quad (10)$$

$$r_{f,1t}^l = \max \left\{ 1, \min \left( r_{f,1t}^l, r_{f,1t}^e \right) \right\} \quad (11)$$

$$r_{f,1t}^e = \max \left\{ 1, \left( 1 - d_{f,1t}^l \right) \frac{X_{f,1t}}{X_{f,PO}} r_{f,1t}^l \right\} \quad (12)$$

where $K_{f,1}$ is the slope of the linear damage degradation, and $r_{f,1t}^l$ is the auxiliary threshold value. $r_{f,1t}^l$ is the damage threshold value at the transition between the linear and exponential damage evolution laws, $d_{f,1t}^l$ and $X_{f,PO}$ are the corresponding value of damage variable and stress.

The detailed derivation process of damage evolution equation can be referred to the literature. The above damage model is carried out by user subroutine VUMAT of Abaqus.

The Weibull distribution law of yarn was compared by simulation and experiment in Figure 4(c). The Weibull distribution of yarn showed a good agreement between the experimental and simulated result, which means that the assumption of the fiber Weibull parameter is appropriate.

**Contact penetration of virtual fiber**

The interference between the virtual fiber surfaces and their surroundings occurs frequently and is connected to contact, which will cause the virtual yarn model to deform under the mechanical effects of prominent level as revealed in Figure 5(a). Most researchers investigated virtual fiber contact by the general contact algorithm implemented in Abaqus/Explicit, which is immensely powerful at detecting colliding/
contacting surfaces for beam elements. However, the penetration problem is challenging for a conventional “Hard” contact formulation, which should be replaced by penalty contact to enforce the contact constraints for quasi-fiber scale modeling. The penalty stiffness is automatically set by software. Therefore, based on research, contact between the virtual fiber and their surroundings (other fibers or compression platens) is imposed on the beam elements only and is defined by penalty contact in this paper. Some specific values have proven sufficient to prohibit penetration in Figure 5(b).

Axial tensile and transverse compressive modeling

A quasi-fiber scale model of yarn tensile simulation was established in Abaqus/Explicit. The diameter of the realistic fiber is 7.5 μm and the calculated cross-sectional area is 44.2 μm². The effective cross-sectional area of the realistic yarn is 0.0864 mm² (approximately). As a result, the realistic yarn contains about 2000 fibers per ply. According to the accuracy and computational efficiency of the model, appropriate amounts of virtual fibers, element length and coefficient of friction are used (see Identification of modeling parameters). The nodes at the start and end of the geometric model are coupled to points RP-1 and RP-2, which are applied same boundary condition with experiment. The coupling point RP-1 is fixed, while the RP-2 experienced deformation increased with a constant velocity, as illustrated in Figure 6(a).

The simulation of compression behavior is performed under quasi-static conditions in Abaqus. The compression is simulated using two Dynamic/Explicit steps by two rigid platens (Rectangle 30×50 mm², rigid shell elements R3D4), which move (displacement-controlled) towards yarn in between with the pre-tension in Figure 6(b). In step-1 the pre-tension was applied, while in step-2 the rigid platens moved to set displacement. The period of the two steps was both 0.5 s. To achieve balance between the modeling precision and computational efficiency and ensure the convergence of the simulation, it is necessary to use mass scaling to increase the mass of the model artificially. During the analysis, a fixed mass scaling factor of 100 was introduced to the virtual fiber model. The distance between two platens is consistent with the experiment. The displacement boundary conditions \( z = 0 \) mm was applied in step-1, and \( z = 0.5 \) mm was applied in step-2 in compression process. Similar to the tensile model, the boundary conditions are applied at
the coupling point. During compression of the yarn, the reaction forces on the platens and the distance between them are used to characterize compressive behavior of yarn.

**Results and discussion**

**Identification of modeling parameters**

Each yarn comprises thousands of fibers, whose interaction is affected by COF input value. Indeed, the mechanical behavior of yarn will be directly affected. However, as the difference in the number of fibers and arrangement style, a yarn model with realistic COF is inappropriate. Re-determining the COF and fiber amount (the volume fraction is consistent) of yarn model are necessary. Besides, decreasing beam element length can enhance the yarn model more accurate, increasing the computational efficiency. Therefore, a balance between modeling precision and computational efficiency must be achieved.

**Coefficient of friction**

Specific frictional constant allowed in the general contact algorithm of the Abaqus/Explicit solver, which determines the interaction between all surfaces.\[42\] It is inaccurate to blindly use the COF, which was measured as the input of simulation. This is due to fact the fibers in realistic yarn are not parallel and straight, which results in potential contact surfaces. A P2-T150 yarn model was established to analyze the effect of different COF on the tensile and compressive response of the simulated yarn in this paper.

The tensile response of P2-T150 yarn simulation with COF - 0.2, 0.35, 0.6 and 0.8 are shown in Figure 7(a). The load is almost unchanged when the COF increases from 0.2 to 0.8 during the tensile test. In addition, the ultimate load has no significant effect on COF. It is because the friction between the fibers increases gradually as the COF increases under the same normal forces, which is far less than the ultimate load of the yarn.

Similar to the tensile simulation of yarn, the compression responses are analyzed for a range of COF from 0.2 to 0.8, see Figure 8(a). The result shows the model with greater COF is subject to more significant compression load at the same platen displacement. Indeed, the
difference between COF - 0.6 and COF - 0.8 is slight. The compression simulations of COF - 0.2 and COF - 0.35 are in good agreement with the experiment. Similarly, as the arrangement has not yet achieved steady (high volume fraction), the compressive load with different COF is same at platen displacement from 0 to 0.2 mm. When the platen displacement increased to 0.2 mm, the compressive load started to change. The amplitude of compressive load with COF - 0.8 is small when the platen displacement from 0.2 to 0.4 mm. As the platen displacement continues to increase, the compressive load is larger than the fiber friction force, and the friction force is weakened, resulting in a sharp increase in the compressive load. However, the realistic COF tends to be lower than the COF obtained by the simulation due to the influence of the contact area and arrangement of the fibers. Generally, two values of 0.35 and 0.2 are appropriate to simulate the compression behavior.

**Virtual fiber count per yarn**

The virtual fibers number of per yarn affects the “fineness” of the simulation. Indeed, more virtual fibers would better represent the realistic behavior of yarn due to the increased
accuracy of the yarn structure. In this paper, the tensile simulation of yarn with 80, 110, 470 and 1070 virtual fibers are carried out in Figure 9, which are about 25, 18, 4.3 and 2 times of realistic yarn, respectively. The tensile simulations with 110, 470 and 1070 virtual fibers closely agree with the experiment, as shown in Figure 7(b). The tensile simulations with 110, 470 and 1070 virtual fibers took about 31, 52 and 107 min of calculation time on the Dell workstation (Precision 7820 Tower). Hence, taking into account calculation efficiency, the model of 110 virtual fibers is more suitable for tensile simulation than other parameters.

The consistency of compression response between simulation and experiment determined is superior, especially in more virtual fibers models (110, 470 and 1070). It indicates that the compaction process is well characterized by the virtual fiber modeling method, even though there are differences between different virtual fiber models. The compression response with the different number of virtual fibers is highly nonlinear, the same as that with different COF, as shown in Figure 8(b). Theoretically, Compression simulation with more virtual fibers is consistent with the experimental results. However, considering the influence of the computational efficiency and accuracy, the model with
110 or 470 virtual fibers will be accepted for compression simulation as the best compromise.

**Element length**

The geometric models of the P2-T150 yarns are generated using three different beam element lengths ($Le$), $Le$ - 0.1, 0.3 and 0.5 mm in this paper. It can be found that the yarn trajectory is relatively rough (which looks like straight line segments, see Figure 10), even though longer elements can reduce computational efficiency.

The tensile simulation of yarn with different element lengths was established in Figure 7(c). The load is transmitted along the axial of the fiber, and the length of element does not affect the mechanical behavior. Hence, it is vital to decrease computational efficiency for tensile simulation of yarn. It took 56, 31 and 18 min to simulate the tensile behavior of $Le$ - 0.1, 0.3 and 0.5 mm, separately. The best compromise between computational efficiency and accuracy can be achieved using the model with a beam element length of $Le$ - 0.3 mm.

The compression behaviors of three element lengths were simulated in Figure 8(c). Similar to other parameters analyses, the platens distance is gradually increased, and the mechanical response of the yarn is highly nonlinear. It has a good coincidence of all curves for a range of platens distance from 0 to 0.4 mm. Otherwise, the compressive load difference between element lengths is significant during the platens distance from 0.4 to 0.5 mm. The $Le$ - 0.1 and $Le$ - 0.3 have a good coincidence with experimental curves. The element length needs to be smaller to conform to the geometry of realistic yarn. In addition, considering the effect of computational efficiency, the model with $Le$ - 0.3 is appropriate for compression behavior.
Simulation and optimization

The Micro-CT images of double-ply yarn with 150 tpm are shown in Figure 11(a) and (b). The numerical models of yarn under appropriate parameters (COF - 0.35, 110 virtual fibers and Le - 0.3) are displayed, as shown in Figure 11(c) and (d). The simulated yarn structure is close to the observation results of the realistic yarn. Numerical models of various twists and ply numbers can be generated by the virtual fiber method. The P2-T150 model as an example was used to compare in this paper.

Deformation under tensile behavior

The tensile response of simulation and experiment of yarns are recorded, and the load-deformation curves are extracted from simulation and experiment. The captured images are shown in Figure 12, which offers the failure modes of yarn. The damage increases with increasing deformation, up to tensile failure at 140 N. When fiber breaks, the fiber suddenly loses its mechanical constraints and spreads to the surroundings. It is because pre-tension is zero after the fiber is damaged, which has a trend of breakage along the direction of untwisting. However, the pre-tension does not significantly affect the inner fibers at the moment of yarn breakage.

Deformation under transverse compressive behavior

The experiment and simulation compression response of the yarn was given in Figure 8. Overall, the curves show an exponentially increasing compressive load with increasing compressive displacement. The geometric images of yarn are shown in Figure 13 to analyze the mechanical behavior and arrangement of fibers under different compressive stages. The fibers are more tightly arranged with increasing platen displacement as expected. Figure 14 shows the cross-sectional image of the yarn model in the middle position. When the yarn is subjected to a compressive load, the fibers preferentially in contact with the platens are rearranged. There is no significant change in the cross-section while the displacement keeps increasing since a compromise between internal stress and compressive load is attained.

The Micro-CT was used to capture the image of yarn during compressive tests. As a comparison, an image analysis method was used to compare section areas of experiment and simulation. Figure 14(a) and (b) represents the cross-section’s image manipulation,
Figure 11. Comparison between (a)-(b) the Micro-CT image of P2-T150, and (c)-(d) the numerical model of the P2-T150 yarn.

Figure 12. Numerical simulation of the fracture of the yarn. (a)-(d) 10%, 50%, 80% and 100% of the ultimate load.

which shows a clear cross-sectional profile. Figure 15(a) illustrates the good agreement between the area of each cross-section of Micro-CT and simulation. Taking into account the deformation of yarn during compression, the fundamental operations in morphological image processing, erosion and dilation, were employed for section area of simulation. In addition, the section area changes periodically within a cycle of twisted yarn. When the yarns are aligned along the direction of compression (see a’ from Figure 15(a)), fiber expands difficultly. The space between fibers mainly contributes to the compressive deformation, and the section area does not change significantly. Hence, the section area at plane a’ is smaller than that at plane b’. Furthermore, quantitative metrics is
Figure 13. Morphology of different stages of compression simulation. (a)-(d) 10%, 40%, 80% and 100% of the compression deformation.

Figure 14. Image analysis method of compressive behavior: (a) realistic cross-section (5 mm), (b) simulated cross-section (5 mm) and (c) quantitative metrics.
utilized to compare the geometric similarity of simulated and realistic yarn. Figure 14(c) indicates the process of generating quantitative metrics. Two profile images under the same section are overlapped based on identical coordinate system. 100 points are collected equally on each profile based on distance-preserving functions. Connecting the points with the same number in two profile images to obtain the Euclidean distance $\rho_m$ of section $m$, which can be calculated using:

$$\rho_m = \sum_{s=1}^{m} \sqrt{(x_{ss} - x_{sr})^2 + (y_{ss} - y_{sr})^2}$$

(13)

where $x$ and $y$ are coordinates of point. The subscripts $ss$ and $sr$ indicate simulated and realistic profile images. The accuracy of two profile images in each cross-section was calculated according to KNN (K-Nearest Neighbors) algorithm, see Figure 15(b).

The yarn models with more ply numbers are established to investigate the effect of ply numbers on the yarn architecture and mechanical response. Figure 16 predicts tensile and compressive behavior of P1-T80 and P2-T80 yarn considering damage to fiber. The ultimate load of tensile behavior increases with the increasing ply number (see Figure 16(a)). Note that, the change rate is not regular, which could be affected by fiber damage. In addition, P2-T80 yarn has a large axial displacement (as shown in Figure 17(a) and (b), which is involved to twist and the number of fibers. The compressive load of P1-T80 and P2-T80 were shown in Figure 16(b). P1-T80 are the same compression tendency with P2-T80, which are non-linear. There is a sharp increase during the whole compression. It is because the initial structure of the yarn is unstable, and the inner fibers are rearranged to be stable (high volume fraction), see Figure 17(d) and (e).

It can be observed tensile load increases with increasing twist in Figure 16(a). Using the P2-T80 as the basis, there exist the change rates of 6.9% between P2-T80 and P2-T150, and the change rates of 28.3% between P2-T80 and P2-T200. The increase in load is mainly due to an interlocking mechanism, that is, the fiber is held together by radial forces and frictions (as shown in Figure 17(b) and (c)). Figure 16(b) predicts a
The compressive load of yarn under different twists, which shows a kinematic response. The compressive load is predominantly determined by the difficulty of rearranging the fibers into a stable structure. The compressive load only increases at high compression displacements when fiber rearrangement becomes jammed, see Figure 17(e) and (f). Unlike the effect of the ply number, the differences in compression response between the different twisted yarns are mainly focused on the higher compression levels. The ultimate load tends to be higher as the twist increases at the same displacement.

**Figure 16.** Effect of different yarn geometries on mechanical behavior: (a) axile tensile behavior and (b) transverse compressive behavior.

**Figure 17.** Axial displacement of yarn with different twists and ply: axial tensile behavior of (a) P1-T80 (b) P2-T80 (c) P2-T200 and transverse compressive behavior of (d) P1-T80 (e) P2-T80 (f) P2-T200.
Conclusions

In this work, an efficient virtual modeling method with stochastic damage properties according to the Weibull distribution was used to build a high precision model of the yarn. The effect of modeling parameters on accuracy of model was investigated based on the Micro-CT technology.

The balance between the modeling precision and computational efficiency can be achieved using the parameters the COF of 0.35, virtual fiber count of 122 and Le of 0.3. The excellent agreement of the simulated and realistic mechanical response was verified based on the image analysis during axial tensile and transverse compressive behavior. An accuracy was proposed to quantitatively analyze variations of fiber based on KNN algorithm.

The influence of parameters of yarn on the axial tensile and transverse compressive behaviors was investigated. The axial tensile and transverse compressive behaviors of yarns with different parameters can be predicted by established yarn model. Also, it describes the deformation and fracture characterization applying a constitutive model with stochastic damage properties. Eventually, the relationship between modeling parameters and mechanical behavior of yarn was established. Textile composite forming involves reinforcements mechanical behavior, which is highly non-linear and depends on several yarn-level factors which is guided by fiber-level interactions. Therefore, before textile composites may develop, the mechanical behavior and deformation of yarn, in particular twist and ply, is necessary to select as sufficient conditions.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The work was supported by China Scholarship Council (CSC 202108120054).

ORCID iDs

Yu Wang https://orcid.org/0000-0002-0622-0325
Ning Wu https://orcid.org/0000-0002-5693-9506
Li Chen https://orcid.org/0000-0002-6534-3309
Peng Wang https://orcid.org/0000-0002-2178-7194

References

1. Wu N, Xie X, Yang J, et al. Effect of normal load on the frictional and wear behaviour of carbon fiber in tow-on-tool contact during three-dimensional weaving process. J Ind Text 2020; 51: 2773S. DOI: 10.1177/1528083720944615
2. Yang Z, Jiao Y, Xie J, et al. Effect of weaving parameters on fiber structure of 3D woven preforms: A Micro-CT investigation. *J Compos Mater* 2022; 56: 2609–2620. DOI: 10.1177/00219983221101173

3. Jiao W, Chen L, Xie J, et al. Deformation mechanisms of 3D LTL woven preforms in hemisphere forming tests. *Compos Struct* 2022; 283: 115156. DOI: 10.1016/j.compstruct.2021.115156

4. Li M, Wang P, Boussu F, et al. Effect of Fabric Architecture on Tensile Behaviour of the High-Molecular-Weight Polyethylene 3-Dimensional Interlock Composite Reinforcements. *Polymers* 2020; 12: 1045. DOI: 10.3390/polym12051045

5. Xiang H, Jiang Y, Zhou Y, et al. Binocular Vision-Based Yarn Orientation Measurement of Biaxial Weft-Knitted Composites. *Polymers* 2022; 14: 1742. DOI: 10.3390/polym14091742

6. Wu N., Li S., Han M., et al. Experimental simulation of bending damage of silicon nitride yarn during 3D orthogonal fabric forming process. *J Ind Text* 2021; 51: 3828S. DOI: 10.1177/15280837211010681

7. Che J, Zhang Z, Hou J, et al. Modeling of fibrous tow transmission considering residual strain and friction. *Text Res J* 2021; 91: 2015–2035. DOI: 10.1177/0040517521993483

8. Xiao S, Wang P, Soulat D, et al. Analysis of the in-plane shear behaviour of non-orthogonally textile reinforcements: Application to braided fabrics. *Compos B Eng* 2018; 153: 159–166. DOI: 10.1016/j.compositesb.2018.07.040

9. Lamon J and R’Mili M. Investigation of flaw strength distributions from tensile force-strain curves of fiber tows. *Compos Part Appl Sci Manuf* 2021; 145: 106262. DOI: 10.1016/j.compositesa.2020.106262

10. Wang J, Zhou H, Liu Z, et al. Statistical modelling of tensile properties of natural fiber yarns considering probability distributions of fiber crimping and effective yarn elastic modulus. *Compos Sci Technol* 2022; 218: 109142. DOI: 10.1016/j.compsitech.2021.109142

11. Hemmer J, Lectez A-S, Verron E, et al. Influence of the lateral confinement on the transverse mechanical behavior of tows and quasi-unidirectional fabrics: Experimental and modeling investigations of dry through-thickness compaction. *J Compos Mater* 2020; 54: 3261–3274. DOI: 10.1177/0021998320912809

12. Xiao S, Wang P, Soulat D, et al. Towards the deformability of triaxial braided composite reinforcement during manufacturing. *Compos Part B Eng* 2019; 169: 209–220. DOI: 10.1016/j.compositesb.2019.04.017

13. Xiao S, Wang P, Soulat D, et al. An exploration of the deformability behaviour dominated by braiding angle during the forming of the triaxial carbon fibre braids. *Compos Part Appl Sci Manuf* 2020; 133: 105890. DOI: 10.1016/j.compositesa.2020.105890

14. Huang J, Boisse P, Hamila N, et al. Experimental and numerical analysis of textile composite draping on a square box. Influence of the weave pattern. *Compos Struct* 2021; 267: 113844. DOI: 10.1016/j.compstruct.2021.113844

15. Xie J, Liu C, Yang Z, et al. Mechanical modeling of textile composites using fiber-reinforced voxel models. *J Compos Mater* 2020; 54: 2529–2538. DOI: 10.1177/0021998319899134

16. Jiao W, Chen L, Xie J, et al. Effect of weaving structures on the geometry variations and mechanical properties of 3D LTL woven composites. *Compos Struct* 2020; 252: 112756. DOI: 10.1016/j.compstruct.2020.112756
17. Gao Z and Chen L. A review of multi-scale numerical modeling of three-dimensional woven fabric. *Compos Struct* 2021; 263: 113685. DOI: 10.1016/j.compstruct.2021.113685

18. Zhou G, Sun X and Wang Y. Multi-chain digital element analysis in textile mechanics. *Compos Sci Technol* 2004; 64: 239–244. DOI: 10.1016/S0266-3538(03)00358-6

19. Wang Y and Sun X. Digital-element simulation of textile processes. *Compos Sci Technol* 2001; 61: 311–319. DOI: 10.1016/S0266-3538(00)00223-2

20. Daelemans L, Faes J, Allaoui S, et al. Finite element simulation of the woven geometry and mechanical behaviour of a 3D woven dry fabric under tensile and shear loading using the digital element method. *Compos Sci Technol* 2016; 137: 177–187. DOI: 10.1016/j.compscitech.2016.11.003

21. Moustaghfir N, El-Ghezal Jeguirim S, Durville D, et al. Transverse compression behavior of textile rovings: finite element simulation and experimental study. *J Mater Sci* 2013; 48: 462–472. DOI: 10.1007/s10853-012-6760-0

22. Yang Z, Jiao Y, Xie J, et al. Modeling of 3D woven fibre structures by numerical simulation of the weaving process. *Compos Sci Technol* 2021; 206: 108679. DOI: 10.1016/j.compscitech.2021.108679

23. Xie J, Chen X, Zhang Y, et al. Experimental and numerical investigation of the needling process for quartz fibers. *Compos Sci Technol* 2018; 165: 115–123. DOI: 10.1016/j.compscitech.2018.06.009

24. Xie J, Fang J, Chen L, et al. Micro-scale modeling of 3D needled nonwoven fiber preforms. *Compos Struct* 2022; 281: 114995. DOI: 10.1016/j.compstruct.2022.114995

25. Xie J, Fang G, Chen Z, et al. Numerical and experimental studies on scattered mechanical properties for 3D needled C/C-SiC composites. *Compos Struct* 2018; 192: 545–554. DOI: 10.1016/j.compstruct.2018.03.056

26. Wang Y, Yu W and Wang F. Experimental evaluation and modified Weibull characterization of the tensile behavior of tri-component elastic-conductive composite yarn. *Text Res J* 2018; 88: 1138–1149. DOI: 10.1177/0040517517698991

27. Revol BP, Thomasse M, Ruch F, et al. Influence of the sample number for the prediction of the tensile strength of high tenacity viscose fibres using a two parameters Weibull distribution. *Cellulose* 2016; 23: 2701–2713. DOI: 10.1007/s10570-016-0974-2

28. Andersons J, Joffe R, Hojo M, et al. Glass fibre strength distribution determined by common experimental methods. *Compos Sci Technol* 2002; 62: 131–145. DOI: 10.1016/S0266-3538(01)00182-8

29. Tian Z, Yan Y, Li J, et al. Progressive damage and failure analysis of three-dimensional braided composites subjected to biaxial tension and compression. *Compos Struct* 2018; 185: 496–507. DOI: 10.1016/j.compstruct.2017.11.041

30. Lu Z, Xia B and Yang Z. Investigation on the tensile properties of three-dimensional full five-directional braided composites. *Comput Mater Sci* 2013; 77: 445–455. DOI: 10.1016/j.commatsci.2013.04.010

31. He C, Ge J, Qi D, et al. A multiscale elasto-plastic damage model for the nonlinear behavior of 3D braided composites. *Compos Sci Technol* 2019; 171: 21–33. DOI: 10.1016/j.compscitech.2018.12.003
32. Chen Z, Wang B, Pan S, et al. Damage analysis of shear pre-deformed 3D angle-interlock woven composites using experiment and non-orthogonal finite element model. *Compos Commun* 2021; 28: 100978. DOI: 10.1016/j.coco.2021.100978
33. Maimi P, Camanho PP, Mayugo JA, et al. A continuum damage model for composite laminates: Part I – Constitutive model. *Mech Mater* 2007; 39: 897–908. DOI: 10.1016/j.mechmat.2007.03.005
34. Chen JF, Morozov EV and Shankar K. A combined elastoplastic damage model for progressive failure analysis of composite materials and structures. *Compos Struct* 2012; 94: 3478–3489. DOI: 10.1016/j.compstruct.2012.04.021
35. Melro AR, Camanho PP, Andrade Pires FM, et al. Micromechanical analysis of polymer composites reinforced by unidirectional fibres: Part I – Constitutive modelling. *Int J Sol Struct* 2013; 50: 1897–1905. DOI: 10.1016/j.ijsolstr.2013.02.009
36. Wu L, Zhao F, Xie J, et al. The deformation behaviors and mechanism of weft knitted fabric based on micro-scale virtual fiber model. *Int J Mech Sci* 2020; 187: 105929. DOI: 10.1016/j.ijmecsci.2020.105929
37. Cherradi Y, Kebir H, Boukhriss A, et al. Mechanical behaviour of 3D monofilament knitted fabrics: Modeling, simulation and validation. *J Ind Text* 2022; 51: 5793S. DOI: 10.1177/15280837221091578
38. Song L, Zhao Y, Li J, et al. Statistics-based full-scale three-dimensional geometric model and fiber length distribution for carbon fiber needle felt. *J Ind Text* 2018; 47: 1543–1567. DOI: 10.1177/1528083717699369
39. Steinbrecher I, Humer A and Vu-Quoc L. On the numerical modeling of sliding beams: A comparison of different approaches. *J Sound Vib* 2017; 408: 270–290. DOI: 10.1016/j.jsv.2017.07.010
40. Ueda M, Nunokawa M and Goto K. Cyclic Tensile Loading Test for a Quartz Fiber Cable of a Deployable Antenna Reflector on Satellite. *Exp Tech* 2018; 42: 421–428. DOI: 10.1007/s40799-018-0251-4
41. Peijian D, Li C, Xiang D, et al. Multiscale analysis on the anisotropic thermal conduction of laminated fabrics by finite element method. *Compos Struct* 2022; 292: 115672. DOI: 10.1016/j.compstruct.2022.115672
42. Daelemans L, Tomme B, Caglar B, et al. Kinematic and mechanical response of dry woven fabrics in through-thickness compression: Virtual fiber modeling with mesh overlay technique and experimental validation. *Compos Sci Technol* 2021; 207: 108706. DOI: 10.1016/j.compsci.2021.108706
43. Bezdek K and Connelly R. TWO-DISTANCE PRESERVING FUNCTIONS FROM EUCLIDEAN SPACE. *Period Math Hung* 2000; 39: 185–200. DOI: 10.1023/A:1004859411072