KINEMATIC MODELING FOR REALISTIC INTERNAL ARCHITECTURAL OF 3D WOVEN CFRP REINFORCEMENT UNIT CELL

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ABSTRACT

A realistic geometric model of 3D woven fabric is developed. Micro-scale repetitive unit cell (RUC) of 3D orthogonal woven fabric is assembled to simulate the dynamic forming process. Truss element is utilised as 1-D element which have fibre-like behaviour. The tensile moduli of fibres are calculated for the actual filaments because of the number and cross-section area of fibre filaments are reduced and enlarged, respectively. Classical Coulomb friction law is used for the tangential behaviours. The periodical boundary condition is applied on two ends of tow. The model results of fabric surface and three mentioned cross-sections are validated with manufacturing composite samples. A similar geometry of 3D woven reinforcement is obtained. This approach paves the road for other predictive model.

1 INTRODUCTION

Three-dimensional (3D) woven composites offer the capacity for higher inter-laminar strength, fracture toughness, damage tolerance due to the Z-binder tow which is through the thickness of reinforcement [1]. However, due to the complex internal geometry of 3D woven composites, the mechanical behaviours are unpredictable precisely. It is loading sensitive which is determined by tows distribution in three directions.

For those reasons, several geometric models for 3D woven composite have been investigated by researchers. Buchanan et al. [2] and Cox et al. [3] used ellipsoidal and Circular as the cross-sections of warp, weft and binder tows. Furthermore, two software packages widely used to model the geometry of woven composites. First, WiseTex was developed by Verpoest and lomov [4] can model several kinds of textile reinforcement with constant cross-section shape. Second, TexGen was developed by Sherburn [5] that individual tow paths and variable cross-sections were feasible in the way of python. But, the internal geometry of composite is always idealized to avoid the complex structure for diverse 3D woven architecture. However, the mechanical behaviours of 3D woven composites are heavily determined by reinforcement micro-structure including fibre orientation and tow waviness.

As is well known, the tow cross-section and waviness are asymmetrical inside composites due to inter-tow tension, compression. In order to obtain a realistic geometry of fabric, the interaction between tows during the forming process should be considered. Wang and Sun [6] proposed an approach called "multi-chain digital element analysis" in which fibre is considered as a flexible 1-D element and each tow is an assembly of fibres. Furthermore, an enriched kinematical beam model developed by Durville [7] which considered deformation of fibre cross-section and bending stiffness. As a similar method, a kinematic model of a 3D woven fabric using beam elements was created in the commercial FE code LS-DYNA by Mahadik and Hallett [8].

Most of the modelling strategies adopted in the literatures take little consideration on manufacturing parameters. In the present model, three sets of tow in terms of warp, weft and Z-binder are regard as group of chain which is represented by multi-segments of truss element. Periodical boundary condition of tow tension was applied on two ends of each tow. Then, the model results of

fabric surface and three mentioned cross-section compared with manufacturing sample. Thus, the objective of this study is to propose a dynamic model relies on many well-defined weaving parameters and validate it against composites sample.

2 MATERIAL

Three sets of tow are oriented to the loom main axis as shown in Figure 1. The warp direction, weft direction and through-thickness direction are referred as x-direction, y-direction and z-direction, respectively. Warp and weft tows are locked by Z-binder and separated into five layers.

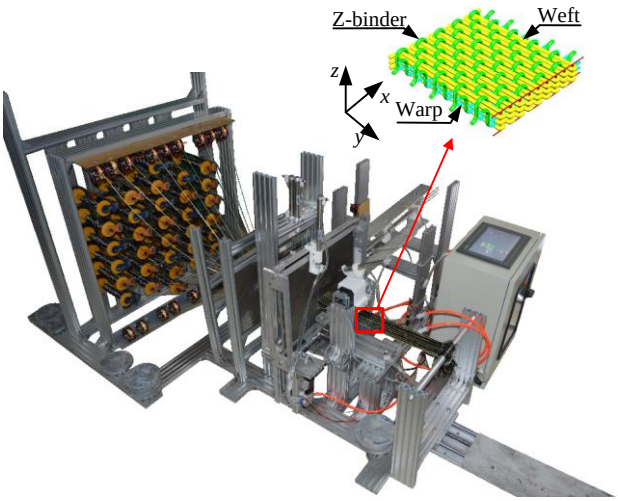

Figure 1: Schematic of 3D orthogonal woven fabric

The 3D orthogonal woven fabric produced on a narrow weaving loom, the fabric parameters, involving fibre type and tow space are listed in Table 1. Carbon (T700) fibre and Kevlar (K29) fibre were employed as warp, weft and Z-binder tows, respectively.

Materials	Number of layers	Type	Number per tow	Fiber diameter (μm)	Density (g/cm^3)	Tensile module (GPa)	Reed density (ends/cm)	Weft tow space (ends/cm)
Weft tow	3	Carbon T700	12K*2	7.3	1.82	230	\	4
Warp tow	2	Carbon T700	24K	7.3	1.82	230	5	\
Z-binder tow	\	Kevlar 29	1K211	12	1.43	62		\

Table 1: Fabric parameters

3 MODEL CONSIDERATIONS

3.1 Fiber bundle representation

Truss element was used as a 1-D element which results in a fibre-like behaviour. The elements are connected by pin-joint which is assumed as Hinges that could not transmit flexural moment. The longitudinal elastic stiffness is considered but bending stiffness is negligible.

3.2 Tensile property

The fiber number has been reduced for each tow as shown in figure 2. So the tensile moduli of truss elements are different from actual filaments because of more gaps appear for the bundle. For example, the area of carbon tow, A_r, can be calculated as:

$$A_r = n_r \cdot a_r \tag{1}$$

Where n_r represents number of filaments, a_r represents cross-section area of each carbon fiber. The gaps in carbon tow are neglected due to micron grade fiber diameter. The cross-sectional area of truss element chains, A_c, can be written as:

$$A_c = n_c \cdot a_c \tag{2}$$

Where n_r represents number of truss element chain, a_c represents area of cross-section of truss element. Therefore, the tensile moduli of truss element, E_c, in the model can be calculated as:

$$E_c = \frac{A_r}{A_c} E_r \tag{3}$$

Where E_r represent the tensile moduli of actual carbon fiber.

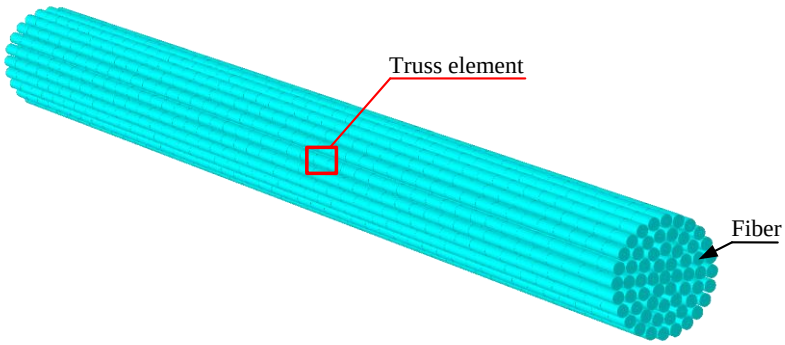

Figure 2: Schematic of 3D orthogonal woven fabric

3.3 Initial loose geometry

Since the textile structure exhibits periodicity, a representation for the whole infinite textile becomes feasible. Hence, an initial loose geometry is generated for fabric structure at the first stage as shown in figure 3. The geometrical parameters are obtained from weaving loom such as reed density, weft tow space. Two principles for the initial loose geometry need to follow: tow overlaps and chains penetrations are unallowed which could induce computation error.

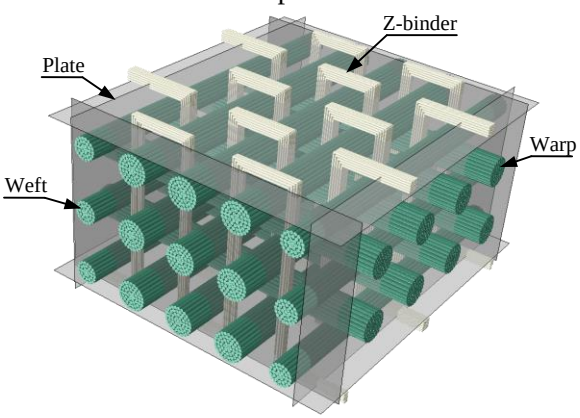

Figure 3: Initial loose geometry of 3D orthogonal woven fabric

3.4 Contact friction

In micro-scale, contact friction occurs not only between tows, but also between fibers. Fiber frictional coefficients were measured by DP-Y151 frictional-meter. The tangential behaviors were performed by Classical Amontons-Coulomb law with constant frictional coefficient as listed in Table 3. The equivalent frictional force, f_{eq}, and critical force, f_{crit}, can be expressed as:

$$f^{eq} = \sqrt{f_1^2 + f_2^2} \tag{4}$$

$$f^{crip} = \mu \cdot p \tag{5}$$

Where f_1 and f_2 are two components in contacted tangential plane and p is the contact pressure. Sliding occurs between two element if $f_{eq} \geq f_{crip}$. The contact pressure can be written as a function of the "overclosure", h:

$$p = p(h) \tag{6}$$

Due to numerous element evolutions during weaving process, the computational time was occupied mainly in the scanning of contact pairs. In general cases, all elements would be scanned to judge the contact state. However, there are only some neighboring tows involved in the contact portion. Based on situation, the contact pairs for each tow are configured individual. As an instead method for manual

handling, python scripting was used for automated assign for the possible contact pairs.

Contact pairs	Frictional coefficients
Carbon to Carbon	0.24
Kevlar to Kevlar	0.29
Carbon to Kevlar	0.26

Table 2: Contact frictional coefficients of each contact pairs.

3.5 Boundary conditions

In weaving process, tension load was applied to the ends of tows in order to straighten the tows. Periodic boundary conditions can be used to the present RVE model. The general expression of periodicity conditions on the boundary is:

$$u = \bar{\varepsilon}_{ik} x_k + u_i^* \tag{7}$$

Where $\bar{\varepsilon}_{ik}$ represents average strains and u_i* is part of periodic displacement components on the boundary surfaces. The displacements of the opposite ends of warp and Z-binder tow along X direction can be written as:

$$u^{j+} = \bar{\varepsilon}_{ik} x_k^{j+} + u_i^* \tag{8}$$

$$u^{j-} = \bar{\varepsilon}_{ik} x_k^{j-} + u_i^* \tag{9}$$

In the above index "j+" and "j-" represent positive and negative x-direction, respectively. Hence, it can be deduced from the above two equation as:

$$u^{j+} - u^{j-} = \bar{\varepsilon}_{ik}\left(x_k^{j+} - x_k^{j-}\right) = \bar{\varepsilon}_{ik} \Delta x_k^j \tag{10}$$

Therefore, the unified periodic boundary conditions can be written:

$$u_i^{j+}(x,y) - u_i^{j-}(x,y) = c_i^j \qquad (i,j = 1,2) \tag{11}$$

Where c_1^1, c_2^2 are the average displacements due to the tension load along the x and y directions.

4 RESULTS AND VALIDATION

The dynamic model described above has been performed in the commercial software (Abaqus). three forming stages could been divided according to the interaction contact as shown in Figure 4(a, b, c). In the first stage, there is no contact happening to warp and weft tows. Then, in the second stage, as applied of tow tensions at all ends of filaments along the longitudinal paths, fibers start to contact and pressure with each other. Contact and sliding were happened in this stage. The last stage is a relative balance stage. Almost no sliding happens and chains are relative static in adhesion state.

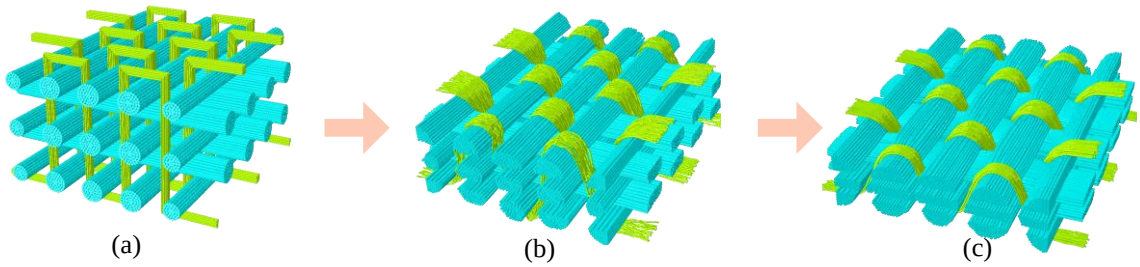

Figure 4: Forming process of 3D woven fabric at different stages: (a) Initial stages, (b) Forming stage, (c) Formed stage.

4.1 Fabric surface

The forming results have been compared with fabric sample from top view as shown in Figure 5(a, b). The fabric dimensions along the x and y direction have been measured and validated with the weaving parameters which have been listed in Table 1. There are 5 ends/cm and 4 ends/cm in warp direction and weft direction, respectively. It is observed that there is a good agreement between the predicted and real fabric surface pattern. This is manifested at the inter-cross region in which weft tow was tightened by the Z-binder tow.

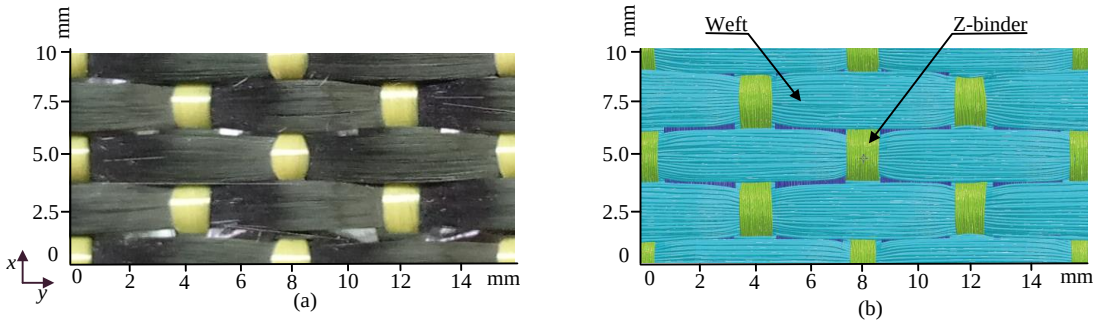

Figure 5: (a) Fabric surface of sample, (b) Fabric surface of model.

4.2 Fabric cross-section

Three cut planes were obtained in order to observe the internal geometric features of present composite sample. For the one plane in y-direction which passes through the weft tow. For the two cut planes in x direction, one passes through the warp tow and the other passes through the Z-binder tow.

In Figure 6(a, b), the warp tow cross section have been outlined with blue lines that could be considered as convex shape. It could be observed that those convex shapes are symmetric distributed in the center line of Z-binder tow.

In Figure 7(a, b), the weft tow cross sections have been outlined with cyan lines. There are three layers of weft tow which are divided by two layers of warp tow. The cross-sections of weft tow in up and button layers are shaped like a bow and distributed symmetrically. The other weft tow cross-section shape which is in middle layer could be considered as rectangle. However, the cross-section of weft tow in the cut plane along Z-binder path changed because of binding effect which induces to nonsymmetrical distribution and shapes the middle layer weft tow cross-section to trapezoid. In Figure 8(a, b), tow waviness of Z-binder has been depicted with green line just like sinusoid curve.

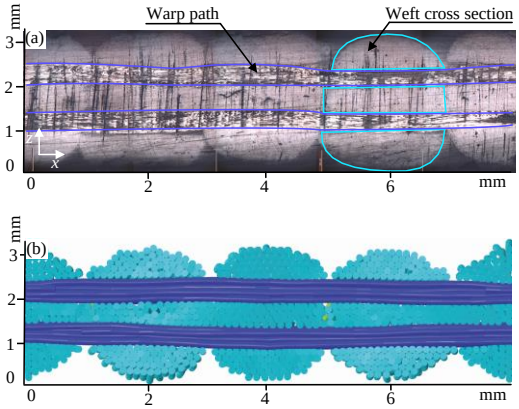

Figure 6: (a) Composite sample cross-section along warp tow, (b) Composite model along warp tow.

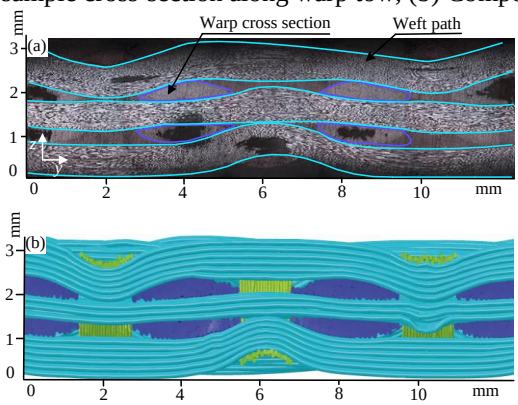

Figure 7: (a) Composite sample cross-section along weft tow, (b) Composite model along weft tow.

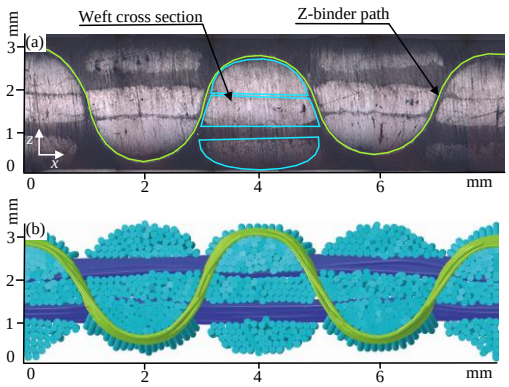

Figure 8: (a) Composite sample cross-section along Z-binder tow, (b) Composite model along Z-binder tow.

5 CONCLUSIONS

A realistic geometric model has been developed in the present paper. Repetitive unit cell (RUC) of 3D orthogonal woven fabric was assembled to simulate the dynamic forming process at the scale of fibre. Three sets of tow in terms of warp, weft and Z-binder are regard as group of chain which is represented by multi-segments of truss element, respectively. Manufacturing parameters in which tow tension were considered as periodical boundary condition applied on two ends of each tow. The model results of fabric surface and three mentioned cross-sections were validated with manufacturing composite samples. The geometry of textile reinforcement is in a good agreement with the composite sample.

ACKNOWLEDGEMENTS

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