Multi-scale modelling of 3D multi-layered braided composite tubes

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ABSTRACT: The mechanical behavior of 3D multi-layered braided composite tubes was analyzed using a multi-scale modelling approach. Considering the braiding parameters and the fiber volume fraction of the composite tubes, firstly a unit-cell of the composites was determined based on the motion of yarn carriers and modeled using TEXGEN software. The unit-cell was imported into finite element software to calculate its meso-scale material properties. In this calculation the yarns in the unit-cell were assumed to be solid constituents without considering each filament in them, i.e., a meso-scale approach was adopted for the yarn modelling. Then, the calculated material properties were used to analyze macroscopic deformation behavior of the composite tubes using finite element analysis. The validity of the current meso- and macro-scale analysis will be discussed for designing composite tubes such as mountain bike (MTB) frames, e.g., in finding optimums of the fiber volume fraction, the braiding angle, and the number of layers.

Key words: multi-layered braided composite tube, multi-scale modelling, finite element analysis

1 INTRODUCTION

Three dimensional tubular composites with complex cross-sections have been utilized to a large extent in military and aerospace application because their toughness and fatigue strength are superior to other composites such as 3D woven and stitched NCF. Several papers reported that for the braided composites the axial yarns are helpful to enhance the shape stability as well as mechanical properties such as damage tolerance and fatigue resistance through the increased fiber volume fraction [1-3].

Geometrical modelling of the 3D braided composite tubes is essential to predicting and further optimizing the performance of final composite parts. Various braiding parameters such as the braiding angle, the number of layers and the number of yarns in them, tows density, and fiber volume fraction needs to be considered for better geometrical modelling. In literature, a geometrical modelling was performed for multilayered braided composites without the axial yarns [4] and the mechanical properties of one and two layered braided composite tubes was calculated analytically [5]. However, the research for multilayer braided composite tubes including the axial yarns has been limited due to their complex geometry, in particular axial yarn.

In this research we aimed to analyze the multi-layered braided composite tubes with the axial yarns adopting a multi-scale modelling approach, i.e., a unit-cell modelling, meso-scale analysis of the unit-cell, and macro-scale analysis of the composite tubes using the meso-scale material properties. Using this approach, the mechanical behaviour of 3D multilayered braided tube was simulated for compression loading case using ABAQUS and simulation results will be compared with experimental ones to assess the validity of the current modelling approach for 3D multilayered braided composite tubes.

2 UNIT-CELL MODELING

2.1 Four-step braiding process

To model the unit-cell in the 3D braided composite tubes, firstly the motion of yarn carriers in a circular braiding bed should be understood. Noting that the carrier sets in the first and last layers are unmovable in the circular braiding machine and the axial yarns do not move radially, the running path of individual yarns in the unit-cell can be determined as follows. At the first step of the braiding cycle, the yarn carriers on the concentric layers move circumferentially, i.e., clockwise for the carriers in the odd layers and counter-clockwise for the even layers. At the second step, the carriers move radially, i.e., inward for the carriers in the odd columns and outward for the even columns. At the third and fourth steps, the carriers will move in the opposite direction to the first and second steps. Considering these carrier motions, the repeating unit can be built as shown in Fig.1, in which the solid lines represent the unit-cell after the 1st and 2nd steps, while the dotted lines does the same thing after the 3rd and 4th steps.

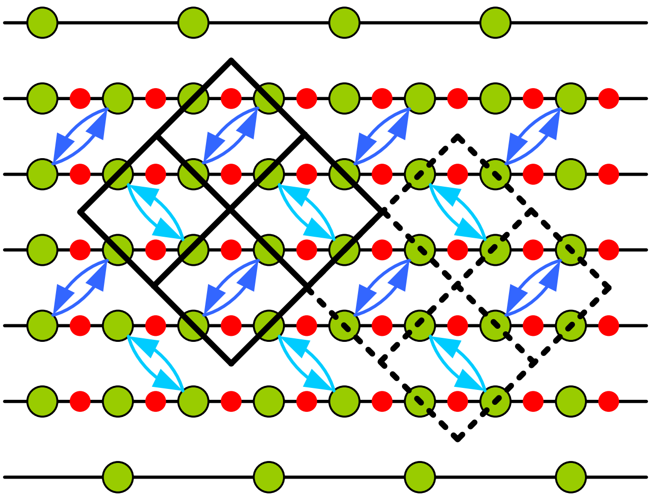

Fig. 1. Yarn carriers in the four-step braiding motion (small circle: axial yarn carriers, bigger circle: braiding yarn carriers)

2.2 Unit-cell geometry

For the geometrical modelling of the unit-cell in the braided composites, two assumptions have been made; in the unit-cell the braiding and axial yarns are straight and their cross-sections are elliptical one with major and minor radii of a and b [4]. With these assumptions the final position of each carrier in the unit-cell can be determined as shown in Fig. 2, in which two braiding yarns in 1/8 unit-cell intersected each other while the axial yarns are located in the y-z plane outside the intersecting yarns. Then, the geometry of the unit-cell can be calculated and visualized using TEXGEN software provided that the running paths of the individual yarns are mathematically described. To prepare finite element model of the unit-cell for meso-scale analysis, actual yarn size in the unit-cell and the unit-cell size in the composite tubes needs to be determined as follows.

2.3 Unit-cell size and fiber volume fraction

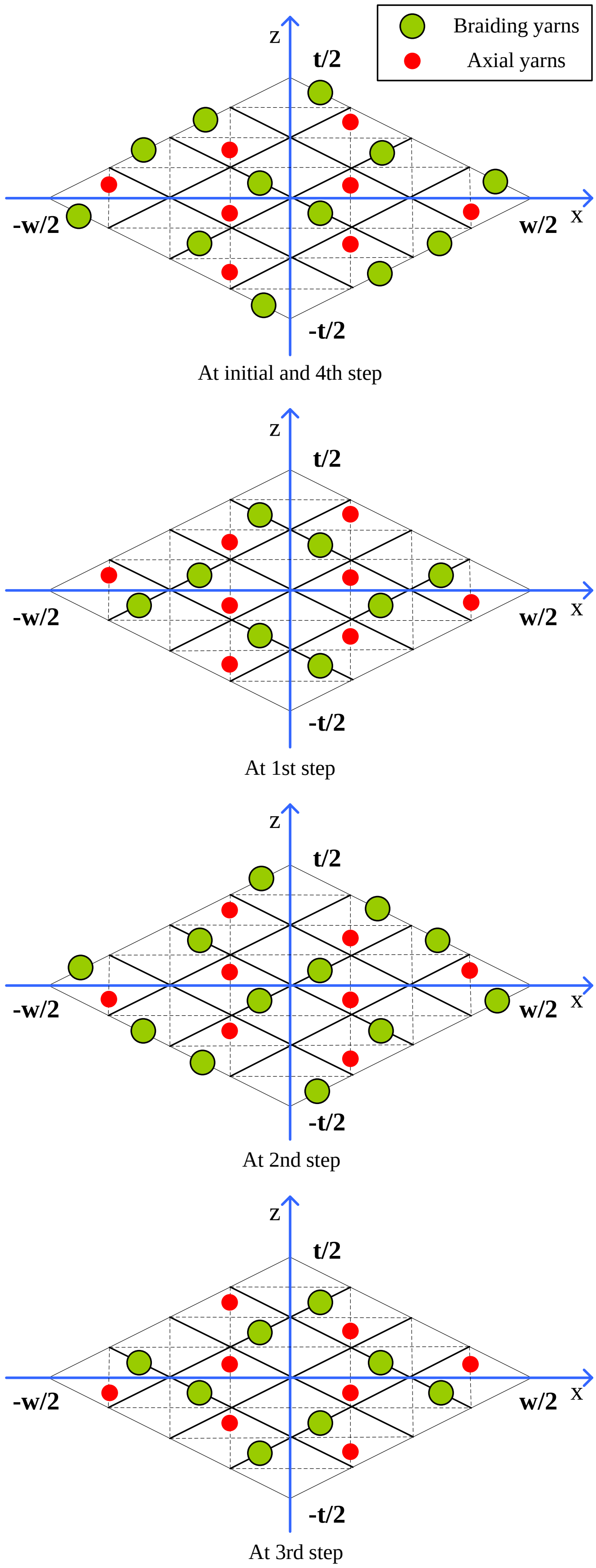

Fig. 2. Running path of braiding and axial yarns at each braiding step

Firstly, the unit-cell size (width (w) x thickness (t) x height(h)) can be easily obtained using the braiding parameters in Table 1 and the physical dimensions of the composites fabricated from the braided preform. In this study, actual composite tube preforms were manufactured through 3D circular braiding machine using UHMWPE fibers and then consolidated using epoxy resin (see Table1).

Table1. Braiding parameters and composite dimensions

braiding parameters	braiding layer (*N*)	5
	braiding yarn carriers per layer (*n*)	72
	axial yarn carriers per layer	72
	braiding angle (Θ)	33°
composite tube	inner radius (R_i)	19.35mm
	outer radius (R_o)	21mm
	tube thickness (T)	1.65mm

Noting that the size of unit-cell is not affected of the axial yarn, the width of the unit-cell was determined considering the number of the braiding yarn in a layer. Furthermore its thickness was obtained from the tube thickness. Finally, the height of the unit-cell can be calculated using the braiding angle as follows.

$$w = \frac{\pi(R_i + R_o)}{n} \times 4$$
$$t = \frac{T}{N+1} \times 4 \qquad (1)$$
$$h = \frac{w}{\tan\theta}$$

The cross-sectional shape of the yarns in the unit-cell was assumed to be elliptical one. The radii of the ellipse were determined by considering the fiber volume fraction in this study. The fiber volume fraction (v) in the unit-cell is calculated from two fiber volume fraction inside the axial (V_a) and braiding (V_b) yarns and the unit-cell volume (V_t):

$$v(\%) = \frac{V_a + V_b}{V_t} * 100 \qquad (2)$$

Each quantity in equation (2) is given by,

$$V_t = w * t * h / 2 \qquad (3)$$

$$V_b = 8(\pi a b h_0)$$
$$where, \quad h_0 = \sqrt{(w/2)^2 + (t/2)^2 + h^2} \qquad (4)$$

$$V_a = 8(\pi a b l)$$
$$where, \quad l = \int_0^h \sqrt{1 + (z')^2}\, dy \qquad (5)$$
$$z = a_1 y^5 + a_2 y^4 + a_3 y^3 + a_4 y^2 + a_5 y + a_6$$

The l in equation (5) represents the length of an axial yarn inside the unit-cell. Since five trace of the axial yarn in a braiding cycle was already determined in Fig.2, the coefficients of 5th order of polynomial can be calculated. Then, with the fiber volume fraction (e.g., 56.39%) of composite tube, the multiplication of the two radii (ab) can be calculated from equations (2). Finally, the geometrical model of the unit-cell is completed with the information described so far as shown in Fig. 3.

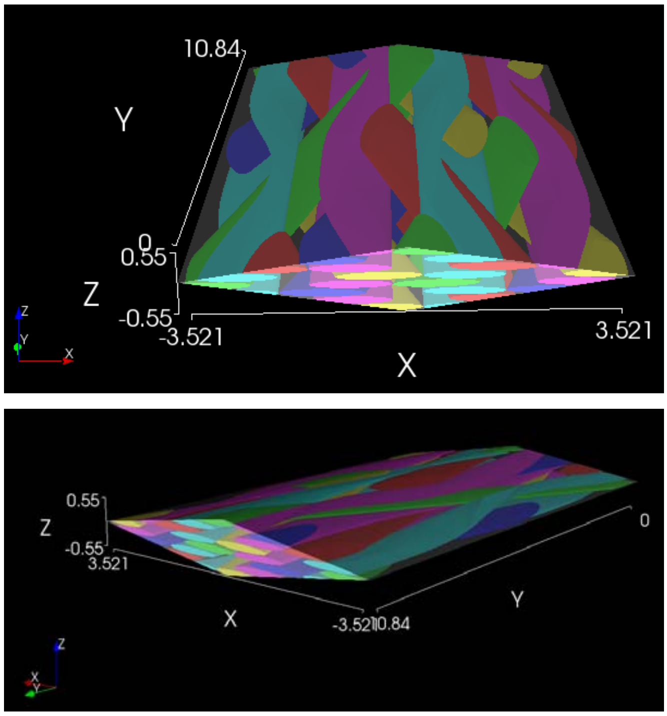

Fig. 3. Geometrical model of the unit-cell

3 MESO-SCALE ANALYSIS

In the three dimensional modelling of 3D multilayered braided composite, it was assumed that the yarns in the unit-cell is transversely isotropic and the resin matrix is isotropic. With the fiber volume fraction (85%) in the tows, their elastic moduli in the axial and transverse directions can be calculated using the rule of mixture in equation (6).

$$E_a = V_f E_f + V_m E_m$$
$$E_t = \frac{E_f E_m}{V_f E_m + V_m E_f} \qquad (6)$$

where, E_a : axial modulus of yarn
E_t : transversal modulus of yarn
E_f : elastic modulus of fiber (Spectra)
E_m : elastic modulus of matrix (Epoxy)
V_f : fiber volume fraction in yarn
V_m : matrix volume fraction in yarn

The elastic modulii of the unit-cell in width and height direction were calculated using FE model, which was prepared by meshing the unit-cell geometry in Fig. 3 and the material properties obtained above.

4 MACRO-SACLE ANALYSIS

From FE analysis of the unit-cell in section 3, two tensile modulii and the shear modulus was obtained. Then, these properties were used to analyze the mechanical behavior of the composite tubes which was modelled using continuum shell element. Fig. 4 shows a simulation result of a composite tube under the compression load. The quantitative comparison of this result with experimental result is in progress and will be presented at the conference.

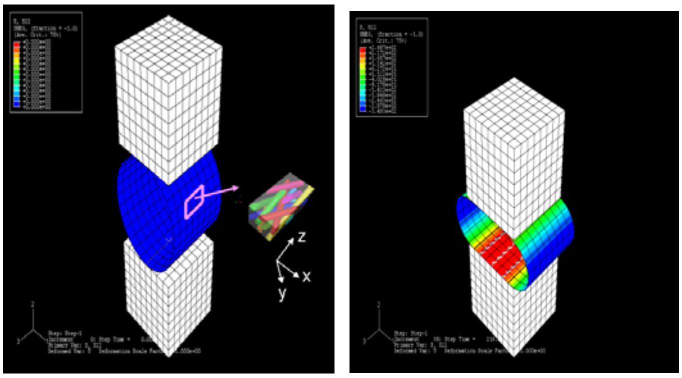

Fig. 4. Macroscopic finite element analysis of 3D multilayered composite tube (compression behavior)

5 SUMMARY

The unit-cell geometry of 3D multilayered braided composite tubes was constructed considering the motion of yarn carriers, the braiding parameters such as the number of the braiding layers, the number of the braiding yarns and the axial yarns in each layer, the braiding angle, and the physical dimensions of the composite tube. Through the finite element analysis of the unit-cell at the meso-scale, basic material properties were obtained, enabling to analyze the mechanical behaviour of the multilayered composite tubes at the macro-scale level. This multi-scale modelling approach may provide an effective mean of designing braided composites tubes considering their integrations into a product such as mountain bike frame.

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