EXPERIMENTAL AND NUMERICAL STUDY OF MECHANICAL PROPERTIES OF THREE DIMENSIONAL FOUR-DIRECTIONAL BRAIDED COMPOSITES

G.D. Fang*, J. Liang, J.C. Han
Center for Composite Material and Structures (Key Laboratory of Science and Technology for National Defence), Harbin Institute of Technology, Harbin, 150080, China
* Corresponding author (fanggd@hit.edu.cn)

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1 Introduction
With the implementation of three dimensional (3D) braided composites in aeronautics, space, marine and automotive fields widely, the mechanical properties of the materials need to be evaluated and analyzed further. Many experiments for 3D four-step braided composites, including uniaxial tensile, uniaxial compressive, shear and bending experiments, have been conducted in some literatures [1-8]. The effect of braid angle, fiber volume fraction and cut-edge on the mechanical behavior of the braided composites has been considered in these literatures. Owing to the integral characteristic of the 3D four-step braided composites, the braid yarns within the braided composites are all continuity. When braid yarn reaches the surface of the composites, it will turn back the interior of the braided composites. Therefore, the interior braid structures which are main braid structures of the braided composites are different from the surface and corner structures. Wu [9] has proposed a three-cell model (interior cell, surface cell and corner cell) to describe the difference of these microscopic geometrical structures. The exterior and interior structures for specimens with different sizes occupy different volume percentages. Usually, the interior structures have great percentage for large size structural components which are manufactured by 3D braided composites. Thus, many scholars have used the interior braid structures to evaluate the mechanical behavior of the 3D braided composites in some theoretical and numerical methods [1, 10-13]. It can be found that the small size braided composites specimens can not obtain the satisfied and valid experimental results.

In order to obtain the mechanical properties of 3D braided composites with only interior braid structures, the cylinder specimens, produced by turning and milling process, only with interior braid structures of the braided composites are utilized in compressive experiments. The different diameters of the specimens are adopted to assess the influence of surface damage on the compressive properties of the braid composites. The different thicknesses specimens with different volume fraction ratios between interior and exterior structures are used in tensile experiments. These specimens with two kinds of interior braid angles, 30° and 45°, are conducted to study the effect of braid angle on the mechanical properties of the 3D four-directional braided composites. The failure and damage modes are analyzed by observing the optical microscopy photographs. And the mechanical properties of the braided composites are simulated by finite element method with a progressive damage model in this paper.

2 Preparation of Experiments
The 3D four-directional braided composites are formed by braid yarns impregnated and solidified with epoxy. The reinforced fibers and matrix are 12K T700 carbon fibers and TDE-85 epoxy resin, respectively. To consider the influence of the percentage of interior braid structures on the experimental results, the specimens with different thickness (H = 3mm, 5mm and 8mm) are adopted. Different diameters (d = 15mm and 17mm) for compressive specimens, removing surface structures by turning and milling process, are adopted to evaluate the effect of surface damage on the compressive properties of the braid composites.

The geometrical sizes and location of strain gages for a tensile specimen are shown in Fig.1. The length of hexahedral compressive specimens $L$ is
The geometrical sizes and location of strain gages for cylinder and hexahedral compressive specimens are shown in Fig. 2a and Fig. 2b, respectively. These tensile and compressive specimens all have two kinds of braid angles, 45° and 30°. It is noted that the braid angles of these specimens are interior braid angle of the 3D four-step braided composites. The experimental results of each group test which has three specimens are the mean value of valid tests in one group test.

**Fig. 1.** Sizes and shape of tensile specimens of the composites.

**Fig. 2.** Sizes and shape of compressive specimens of the composites.

### 3 Experimental Results

#### 3.1 Tensile and Compressive Characteristics

Tab. 1 shows the tensile characteristics of the braided composites with different braid angles and specimen thickness. The number is composed of the braid angle and thickness in Tab. 2. For instance, 303 denotes the specimen with 30° braid angle and 3mm thickness. It can be found that the longitudinal tensile modulus decreases with the increase of thickness, while the Poisson’s ratio increases with the increase of thickness.

**Tab. 1.** Tensile experimental data of the composites.

<table>
<thead>
<tr>
<th>Number</th>
<th>Modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>303</td>
<td>69.83±0.09</td>
<td>0.54±0.006</td>
<td>1158.8±6.06</td>
</tr>
<tr>
<td>305</td>
<td>67.54±0.23</td>
<td>0.61±0.006</td>
<td>1260.4±4.14</td>
</tr>
<tr>
<td>308</td>
<td>65.78±0.34</td>
<td>0.66±0.010</td>
<td>1220.5±2.46</td>
</tr>
<tr>
<td>453</td>
<td>33.15±0.36</td>
<td>0.57±0.010</td>
<td>411.4±2.48</td>
</tr>
<tr>
<td>455</td>
<td>30.16±0.14</td>
<td>0.63±0.015</td>
<td>485.5±3.15</td>
</tr>
</tbody>
</table>

Tab. 2 shows the uniaxial compressive experimental results. The number is composed of the braid angle and diameter of specimen. For instance, 3015 denotes the specimen with 30° braid angle and 15mm diameter. It can be found that the compressive strength is large lower than the tensile strength listed in Tab. 1. In addition, the compressive modulus is lower than the tensile modulus as well. The compressive modulus of specimen with big diameter is lower than that of specimen with small diameter.

#### 3.2 Damage and Failure Mechanisms

It can be found from Fig. 3 that the breakage of braid yarn within specimen with 30° braid angle appears lamellar characteristic, while the fracture of braid yarn within specimen with 45° braid angle is flat.

**Fig. 3.** Micro tensile failure mode of braid yarn in specimen with different braid angle.

**Fig. 4.** Micro compressive failure mode of braid yarn in specimen with different braid angle.
Fig. 4 shows the fiber bundles within specimen with 30° braiding angle appear step-like failure mode. And the normal of fracture plane of fiber bundles within specimen with 45° braiding angle is parallel to the fiber longitudinal direction.

4 Geometry model

Because braided preforms of the 3D four-directional braided composites are formed by four-step method, the geometrical configuration of the braided composites exhibits periodic characteristics in the micro-scale as shown in Fig. 5a. A smallest RVC can reproduce the geometrical structure of the braided composites when it is piled up periodically. In this paper, an RVC including four braid yarns with different directions as shown in Fig. 5b is chosen from the interior braid structure of the braided composites to analyze their mechanical properties. The Fig. 5c shows the sizes of the cross-section of the braid yarn in the RVC. The braid angle \( \gamma \) and the height \( h \) of the RVC can be measured by microscopic image analysis. The relations of geometrical parameters indicated in Fig. 5b and Fig. 5c of the RVC can be expressed as follows:

\[
\begin{align*}
L_a &= 2b \cos \gamma \\
L_b &= 2b - (2a - L_a) \cos \gamma \\
L_m &= 4b \cos \gamma \\
\end{align*}
\]

where the height of cross-section \( h \) can be determined by K-number (a thousand fiber is counted as 1 K.) of yarn and cross-section area \( A \).

Due to the periodic characteristic of the braided composites, the periodical boundary conditions should be applied in the finite element model. It is necessary to keep forces continuity and displacements compatibility of the opposite faces of the RVC. Thus, the opposite surfaces of the RVC should have the same number nodes in the process of meshing the RVC. Every two nodes of the opposite surfaces form a coupling displacement constraint by Fortran pre-compiler code. The detail periodical boundary conditions of the RVC are provided in Ref. [12, 13].

5 Numerical Results

a) 45° braided composites

Fig. 6 is the tensile stress-strain curves for 30° and 45° braided composites. It can be found that the numerical results have some different from the experimental results. The slope of predicted curve is lower than that of experimental results. With the increasing the thickness of specimens, the slope of curves decreases gradually. Therefore, the phenomenon can be attributed that the exterior
structure of the specimens is not considered in the simulation.

Initially, the compressive stress-strain curve as seen in Fig. 7 of the 45° and 30° braided composites displays a relatively linear behavior. With continued loading, the curve for 45° braided composites becomes progressively nonlinear, reaches the maximum stress and then decreases slowly, while the curve for 30° braided composites decreases rapidly to a certain value after the peak loading.

6 Conclusions

The mechanical properties of the three dimensional (3D) four-directional braided composites are studied by experimental and numerical study. The experimental results are in good agreement with the numerical results. The strength of the braided composites with different braid angle is controlled by the different microscopic failure modes, which can be reproduced and recognized at length by numerical method. Similarly, it will be a valid tool to study the progressive damage and failure of other braided composites with different braid methods. In addition, this research method can be extended to study the mechanical properties of 3D braided composites under complex loadings further.

References