EXPERIMENTAL AND ANALYTICAL STUDY OF BENDING BEHAVIOR OF TEXTILE YARN UNDER EXTERNAL PRESSURE

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ABSTRACT

The yarn in textiles exhibits high flexibility compared with continuous material due to friction and slippage between fibers. Understanding the highly nonlinear bending behavior of the textile yarn is vital for the prediction of the mechanical response of textiles during forming. The contact pressure of the yarn in the preform is variable, which significantly influences the frictional behavior between the fibers and the bending behavior of the yarn. To measure the bending behavior of textile yarn under different contact pressure, bending tests are performed under different external pressures applied through a specially designed test rig. The carbon fiber yarn was enclosed in a sealing bag and evacuated at different levels to obtain different contact pressure. The evacuated specimens were sealed with a heat-sealing machine to maintain the external pressure during the bending test. The results of the bending tests show that the specimens exhibit the same initial bending stiffness as the classical beam theory predicted, regardless of the level of the applied external pressure. With the increase in the bending load, the slippage between fibers occurs and the bending stiffness starts to degrade. The external pressure delays the occurrence of fiber slippage leading to a higher maximum bending load. Based on the classical beam theory, an analytical model considering fiber slippage is proposed, which is able to accurately predict the bending stiffness degradation of the textile yarn under different external pressure. This research provided new insights into the yarn bending behavior with the consideration of external pressure. The experimental and analytical results can be used in yarn-level modeling of textiles during forming to improve the predicted mechanical responses of textiles.

1 INTRODUCTION

Due to the increasing performance requirements of composite structural components, especially in the field of aeronautics and astronautics, the textile technique is used to increase stiffness and strength, tailorable structural properties, and high damage tolerance [1]–[3]. Different from continuous material, the yarn in textiles exhibits high flexibility due to friction and slippage between fibers, making the textile reinforcements have excellent drapability. Understanding the mechanical behavior of the textile yarn is vital for predicting the forming process and optimizing the textile structure [4]–[6].

The mechanical behavior of the single yarn can be studied with the experimental methods designed for the fabrics, including Peirce’s cantilever-bending test [7], Kawabata’s Evaluation System (KES), and the three-point bending tests. In Peirce’s cantilever-bending test or vertical cantilever-bending test of the woven fabrics, the specimens are fully fixed at one end and loaded at the other end [8], [9]. In these cantilever-bending tests, the deflections of the deformed specimens are captured for the bending behavior analysis. The straightforward test procedure makes the cantilever-bending test widely used for revealing the bending behavior of fabrics [10]–[12]. However, the effect of the specimens’ gravity and the deflection measuring method influence the accuracy of the test. The KES imposes the curvature of the specimens by rotating the gripper, which is capable of capturing the nonlinear moment-curvature responses and hysteretic behavior during loading-unloading cycles of fabrics [13]. The KES has high accuracy but cannot be used for the test of multi-ply reinforcements. The three-point bending tests that are frequently used for measuring the bending behavior of continuous materials can be improved for measuring the bending behavior of fabrics [14]. However, the three-point bending method will lead to distinct errors when the bending loads are not much greater than the gravity of the specimens, limiting its use for tests of specimens with small bending stiffness.

The above-mentioned experimental methods can be used to obtain the bending behavior of the single yarn with no consideration of the interaction between yarns in the reinforcements. While the yarn-to-yarn interaction including the friction and the contact pressure spread all over the reinforcements, caused the existing experimental methods to be insufficient for characterizing the mechanical behavior of the yarn in the reinforcements. The different bending behavior of the textile yarn compared with the continuous materials is caused by the friction and slippage between fibers which are determined by the contact pressure of the yarn. The effect of the external pressure on the bending behavior of textile yarn has not been investigated in the existing study.

The present paper primarily aims to provide new insights into the yarn bending behavior with the consideration of external pressure and is structured as follows.

Section 2 describes the employed experimental procedure and associated experimental setup. The carbon fiber yarn is innovatively enclosed in a sealing bag and evacuated at different levels to obtain different contact pressure. The evacuated specimens are sealed with a heat-sealing machine to maintain the external pressure during the three-point bending test. Section 3 presents the test results and the results of classical beam theory. An analytical model considering fiber slippage is proposed in Section 4, which is able to accurately predict the bending stiffness degradation of the textile yarn under different external pressure. The main conclusion drawn from the work are outlined in Section 5.

2 EXPERIMENTS

2.1 Specimens preparation

The tested specimens are consisting of flatten Toray T700-12k carbon yarns, and the fiber properties are given in Table 1. Due to the thickness of a single T700-12k yarn is fairly small (about 0.03mm), the yarns are stacked to increase the bending stiffness of the specimens. The stacked yarns were enclosed in a sealing bag and evacuated at different levels to obtain different contact pressure. Preparing process of the specimens is shown in Figure 1. Firstly, enclose the stacked yarns in the sealing bag. The sealing bag has air-guide grid lines on the internal surface to connect the opening end and the blind end. Secondly, a vacuum pump is used for air exhaust, and two vacuum gauges are placed on the opening end and blind end respectively to monitor the pressure difference. When the vacuum gauges steadily show the same vacuum degree, the air exhaust completed. Thirdly, the evacuated specimens were sealed with a heat-sealing machine to maintain the external pressure during the bending test. Finally, the specimen is prepared and ready for the bending test.

As shown in Figure 1, employing sealing bag with an air-guide grid liner and measuring air pressure on the blind end are two remarkable operations to improve the accuracy of the obtained external pressure. Because the enclosure space will form around the specimen when the smooth sealing bag is used, and the external pressure on the specimen will not equal to the pressure on the opening end.

Table 1: Properties of the tested specimens.

Properties	Value
Tensile Modulus of Fiber	240 GPa
Tensile Strength of Fiber	4900 MPa
Density	1.8 g/cm^3
Friction coefficient	0.4
Filament Diameter	7 μm
Yield	800 g/1000m
Width	25 mm
Length	200 mm
Number of Plies	60
Total Thickness	3.05 mm
Thickness of sealing bag	0.13 mm

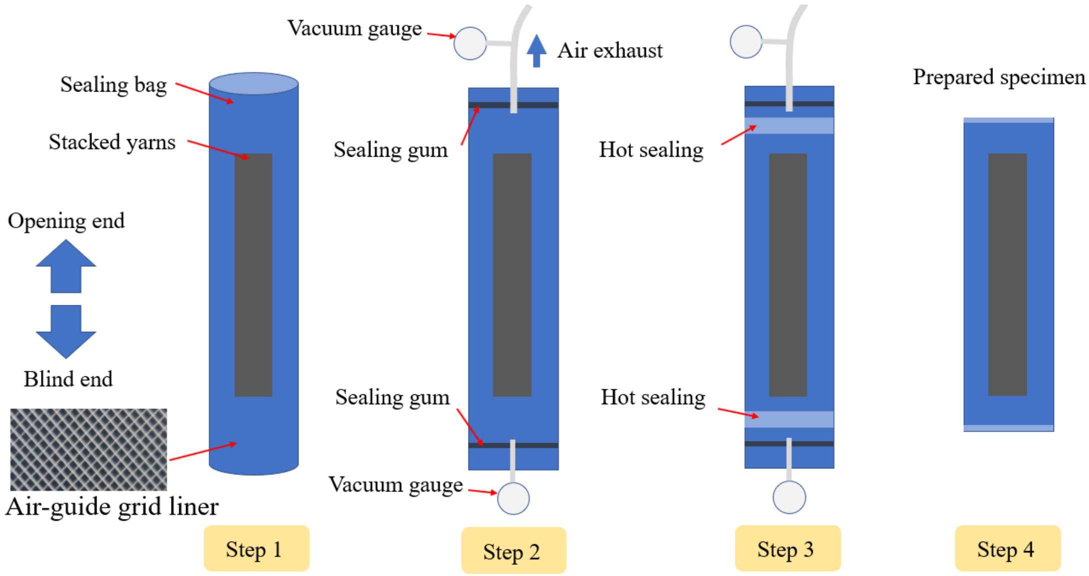

Figure 1: Preparing process of the specimens.

2.2 Test setup

A custom-designed apparatus based on the ASTM-D7264 standard test method was employed in this work. Although the external pressure has been applied on the specimens, the bending stiffness is quite small, requiring a load cell with small measurement range. The measurement range of the adopted load cell is -50-50 N. As shown in Figure 2, the load cell is installed on the sliding table connecting the loading nose. The sliding table is driven by a stepping motor and moves at speed of 1.8 mm/s. The reaction force of the load cell is recorded at a frequency of 0.25 s.

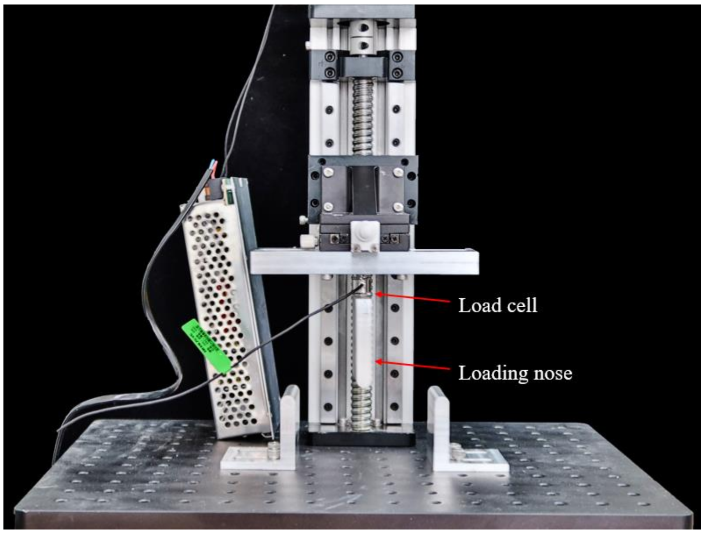

Figure 2: Custom-designed apparatus for bending test of textile yarn.

3 ANALYTICAL MODEL

Before slippage occurs, the specimen is integrity, and the bending stiffness can be defined with the Euler–Bernoulli beam theory as follows:

$$EI_{ini} = \frac{Ebh^3}{12} \tag{1}$$

where E is the tensile modulus of the specimen, b is the width, and h is the thickness of the specimen. During three-point bending test, the inter-layer shear stress can be assumed as constant along the width direction, then the inter-layer shear stress can be expressed as:

$$\tau = \frac{F_s S_z^*}{bI_z} \tag{2}$$

Where F_s is the shear force of the section, S_z^* is the static moment of the area beyond the range of y.

In the initial stage when the inter-layer shear force is less than the force of friction, no slippage occurs. With the increase of shear force and the bending load, the shear force of the neutral surface will firstly reach the maximum static friction force, and the slippage occurs. In the analytical model, when slippage occurs between two layers, the integrated section is divided into two sub-sections, and the bending stiffness of the specimen is degraded as:

$$EI_{total} = E(I_{sub}^a + I_{sub}^b) = E(\frac{bh_a^3}{12} + \frac{bh_b^3}{12}) \tag{3}$$

Where I_{sub}^a and I_{sub}^b are moment of inertia for the sub-sections, h_a and h_b are thickness of the sub-sections. As bending load continues to increase, the two sub-sections bear the increment of load respectively, and the shear stress between the sub-sections remain constant. When the maximum shear force of the sub-sections reaches the maximum static friction force, the sub-sections are continually divided into new sub-sections. Finally shear force between layers all equal to the maximum static friction force, and the bending stiffness of the specimen is fully degraded. The fully degraded bending stiffness is expressed as:

$$EI_{total} = \sum_{i=1}^{n} \frac{Ebh_i^3}{12} \tag{4}$$

In practice, the slippage will occur in the local area of between layers, rather than the whole area between layers. The model above will lead to excessive degradation of the bending stiffness. To avoid excessive degradation, an exponential degradation law is adopted. When shear force between two layers reach the maximum static friction force, the bending stiffness varies as an exponential function of the shear force. A parameter is used in the exponential function to define the degradation rate, which is set as 150 in this paper. The fully degraded and exponential degraded bending stiffness of the tested specimen as a function of shear stress are plot in Figure 3.

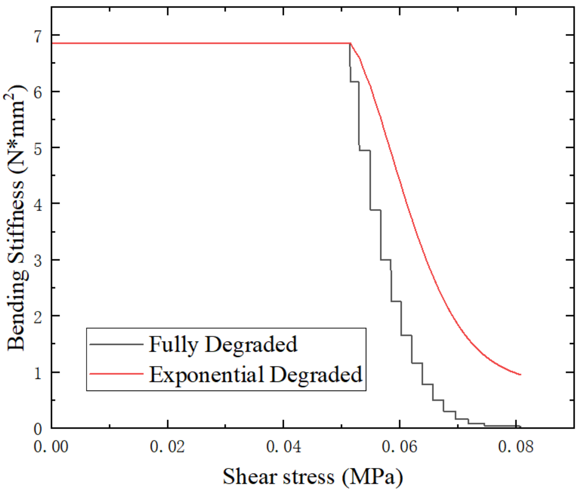

Figure 3: Fully degraded and exponential degraded bending stiffness of the tested specimen as a function of shear stress.

4 RESULTS

The displacement-load curves of the experimental tests and two types of analytical models are shown in Figure 3. The external pressure of group A is 0.096 MPa, and that of group B is 0.048 MPa. The results show that the specimens exhibit the same initial bending stiffness as the classical beam theory predicted. With the increase in the bending load, the slippage between fibers occurs and the bending stiffness starts to degrade. The external pressure delays the occurrence of fiber slippage leading to a higher maximum bending load.

The two types of analytical model can accurately predict the initial bending stiffness and the start of the bending stiffness degradation. Due to the excessive degradation of the bending stiffness, results of the analytical model whose bending stiffness is fully degraded when slippage occurs are much lower than the experimental results. The analytical model with an exponentially degraded bending stiffness agrees well with the experimental results in the whole load process.

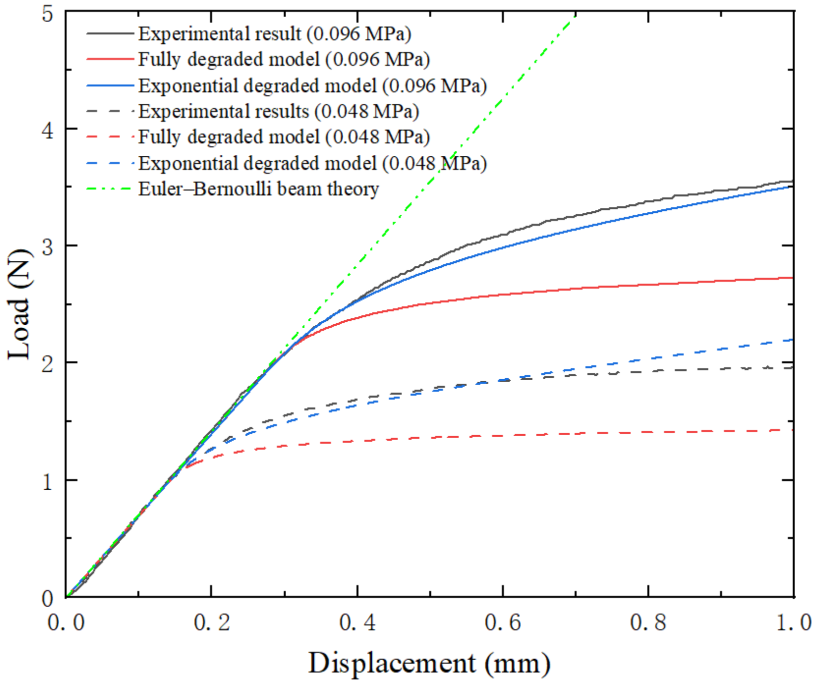

Figure 4: Experimental and simulation results of the bending tests with the external pressure of 0.096 MPa and 0.048 MPa.

5 CONCLUSIONS

In order to understand the highly nonlinear bending behavior of the yarn during textile forming, this paper developed a new three-point bending test to characterize such behavior by introducing external pressures on the specimens. The tested yarn was enclosed in a sealing bag and evacuated at different levels to obtain different external pressures. The bending tests of the specimens under 0.096 MPa and 0.048 MPa are successfully preformed. Based on the Euler-Bernoulli beam theory, an analytical model is proposed which considers the slippage of the fibers. The results of the tests show that the Euler-Bernoulli beam theory can accurately predict the initial bending stiffness of the specimens. With the load increase, the shear stress between the yarns increases and reaches the critical friction stress. When slippage occurs, the bending stiffness of the specimens decrease with the increase of load. The external pressure delays the occurrence of fiber slippage leading to a higher maximum bending load. The results also show that the proposed analytical model is able to accurately predict the bending stiffness degradation of the textile yarn under different external pressure. This research provided new insights into the yarn bending behavior with the consideration of external pressure, which will help to understand the behavior of the yarn in textiles. The experimental and analytical results can be used in yarn-level modeling of textiles during forming to improve the predicted mechanical responses of textiles.

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