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ORIGINAL ARTICLE

Influence of pretension on mechanical properties of carbon fiber in the filament winding process

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Abstract The present study has investigated the effect of the roving tension (pretension force) on the strength of continuous carbon fiber used in the Filament Winding (FW) process. Pretension force is generally applied to composite products manufactured by FW technology to lay out the carbon fiber onto the cylindrical tube in a correct way. However, a considerable amount of damage occurs in the fibers during fiber movement trough pulleys in the pretension unit. A winding system was designed to simulate the process to understand the effects of the parameters such as roving tension, pulley diameter, and contact angle between pulley and fiber. Several experimental tests have been performed by changing pulley diameters and tension forces to understand the effect of these parameters. According to these experiments, the angle between the pulley and the amount of force applied to the carbon fiber generate the damage on the carbon fiber. Tension tests were also conducted to evaluate the strength of the damaged and undamaged carbon fiber. Experimental results indicate that the tensile strength of carbon fiber is reduced by 10 to 43% because of a change to the roving tension (pretensioning) parameters.

Keywords Carbon fiber · Mechanical properties · Filament winding · Roving tension · Strength loss

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1 Introduction

Composite structures which consist of fiber and resin are widely used in industrial areas as new structural materials. Some composite structural parts are manufactured from carbon fibers, which are used to produce mechanical parts where lightness and high strength are required. Some very important industrial sectors such as transportation, aerospace, automotive, electronic packaging, and biomedical and sporting goods are increasingly using composite products more often than before. High-pressure vessels, rotating shafts, robot arms, and other sports and leisure goods are examples of the use of composite materials.

One of the most important composite forming processes is the Filament Winding (FW) process, which requires smooth path control of the continuous fiber. The pretensioning unit is an important part of the filament winding machine. The task of the pretensioning unit is to keep the pretensioning force on the carbon fiber at a specific range under various tension forces during the winding process. Strain to the brittle structure of the carbon fiber by the pretensioning unit creates the important need for the optimization of the parameters on the pretensioning unit to lessen damage on the fiber roving.

A number of scientists have studied various structural problems related to filament-wound, metal-lined cylinders under internal pressure or impact [2–11]. Although all of these studies focused on the product strength, none addressed the pretensioning unit and its effects. Calius and Springer [12] studied a model that described the thermal, chemical, and mechanical behavior of filament-wound thin cylinders in light of the three process variables: winding speed, fiber tension, and ambient temperature. Calius et al. [13] focused on the analytical and experimental study to further corroborate a model developed by Lee and Springer for simulating the manufacturing process of filament-wound composite cylinders. Lee and Springer [8] developed a model that describes the filament winding process of composite cylinders. This model identifies the significant process variables such as winding speed, fiber tension, and applied temperature to the thermal, chemical, and mechanical behavior of the composite cylinder and the mandrel. Lee and Springer [7] studied the calculation in graphite-epoxy composite cylinders during the winding and subsequent curing by using the Lee-Springer filament winding model temperatures, degrees of cure, viscosities, stresses, strains, fiber tensions, fiber motions, and void diameters.

Cohen [3] studied the manufacturing and design variables that affect composite vessel quality, strength, and stiffness. Mertiny and Ellyin [1] investigated the influence of the applied tow tension during filament winding on the physical and mechanical properties of glass fiber-reinforced polymeric composite tubular. Hwang et al. [4] conducted experimental tests using an analytical approach to verify the size effect on the fiber strength of a composite pressure vessel. The effect of pretension is found to be negligible in some studies [14]. Koussios and Bergsma [14] performed several experiments corresponding to the variation of typical filament winding-related process parameters: fiber speed, roving tension, roving dimensions, wet versus dry winding, and surface quality of the mandrel. They neglected the effect of the pretension in their study. In other filament winding process experimental studies [15–20], researchers controlled the various parameters through robotic applications or neural network methods to optimize the winding conditions. For example, Li [21] controlled the tension force in filament winding using a fuzzy neural network. In this study, we demonstrate that the system can not only exhibit desired dynamic performance but can also adapt to the wide range of speed and tension force changes by a proper servo motor and winding operation. However, the effect of pretension is assumed to be negligible in some studies. For example, Koussios and Bergsma [14] performed several experiments corresponding to the variation of typical filament winding-related process parameters: fiber speed, roving tension, roving dimensions, wet versus dry winding, and surface quality of the mandrel. They neglected the effect of the pretension in their experiments.

The principal aim of this study is to investigate the effect of pretensioning on the fiber strength loss. An experimental winding setup was developed to simulate the process of pretensioning in filament winding processes to carry out this investigation. In this experimental setup, pretension force can be easily adjusted by changing the pulley positions and the pulley diameters. Several experiments were carried out to understand how the strength of carbon fiber is reduced during the passing of fiber inside the pulleys of the tensioning unit.

2 Design of the winding system

This study investigates the effect of pretension force to determinate what degree the strength of carbon fiber is affected when the carbon fiber passes through the pulleys of the pretensioning unit during the winding process. A winding system [22] was designed to simulate the process of pretensioning in a filament winding machine to understand the effect of the parameters of the pretensioning unit.

The winding system was designed under the tree unit as shown in Fig. 1. The first unit is the magnetic brake unit (MBU) (Fig. 1a), the second unit is the pretensioning unit (PU) (Fig. 1b); and the third unit is the winding unit (WU) (Fig. 1c). The MBU is designed to adjust and monitor the pretension force during carbon fiber winding. The PU is designed with five pulleys whose positions can be changed to determine the roving tension parameters, such as the filament winding machine's pretensioning unit. The WU is designed to pull the carbon fiber to carry out the winding process. The winding process starts when the WU begins to pull the carbon fiber. During the winding process, the pretension force can be adjusted using the MBU. This winding process can be repeated for each value of the pretension force and for each position of the pulleys.

Following the winding process, specimens are taken out from the mandrel and cut for testing by the tensile testing

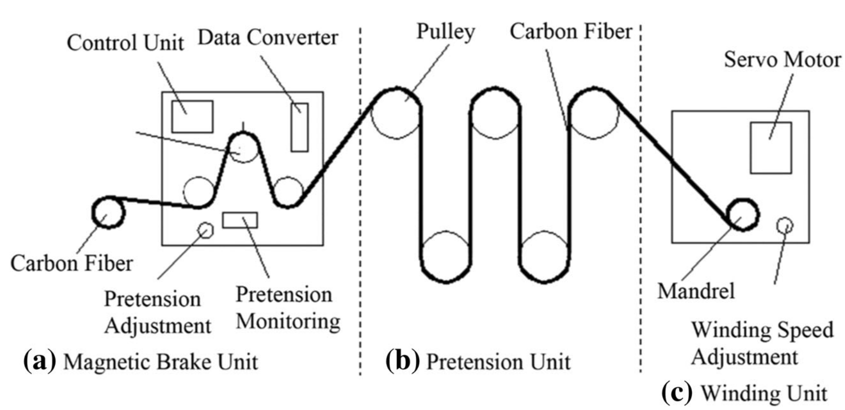

Fig. 1 Schematic drawing of a filament winding pretension system

machine to determine the variations in the strength of carbon fiber based on the process parameters.

3 Experimental work

The prediction of the mechanical properties of the carbon is very important in making suitable right composite structure designs. The experiment was conducted to determine how the carbon fiber's mechanical properties are affected in the pretensioning unit during the winding process.

3.1 Modeling the coefficient of friction

Figure 2 shows the positions of the pulleys (x and y), tension forces (T), and the contact surface angles (θ) during the winding process. As shown in this figure, fiber tows pass from the pivoting pulleys which are supported by a ball bearing during the winding process.

The winding process starts when the servo motor starts to pull the carbon fiber on the force T_6 that generates the force T_1 on the other direction.

As shown in Fig. 3 illustrating the friction between the carbon fiber and pulleys, the formula for the static tensional force (T_1) and pulling force (T_6) must create the friction force given by Eq. 1.

$$\Delta T_s = \mu_s . \Delta N \tag{1}$$

The general static tensional force equation which is given in Eq. 1, can be adapted for a pulley tension system that composed of 5 pulley as follow;

$$T_6 = T_1 e^{\mu\theta} \tag{2}$$

But, the contact surface (θ) is not the same for all the pulleys. For this reason, θ was accepted as total contact angles and can be calculated the following equations:

$$T_6 = T_1 e^{\mu . \Sigma\theta} \tag{3}$$

Simply obtain.

To calculate the coefficient of friction, T_1 is measured from MBU by load cell and T_6 measured using another load cell connected to commercially available data logger of KYOWA-UCAM 21 measurement and data acquisition system. The surface roughness of the pulleys as roughness average (Ra) is 0.20 μm. According to the measurement, friction coefficient is calculated as 0.41 using Eq. 3.

3.2 Design of the winding conditions

The experimental winding process was carried out using eight conditions of pretensioning to determine the extent of damage to the carbon fiber. The diameters of pulleys were determined as they would be on an actual pretensioning unit of the filament winding machine. Therefore, the diameter of the pulleys on the pretensioning unit varies between 30 and 78 mm.

As shown in Table 1 and Fig. 2, a change in both the pulley's positions (by changing y) and the pulley's diameter determines the total contact angles ($\sum\theta$). The total contact angle affects the strength of the carbon fiber because this angle determines the bending stresses and friction between the carbon fiber and the aluminum pulleys.

Following the winding process, wound dry carbon fiber (CF) tows are taken out from the mandrel and cut as shown in Fig. 4. The tensile specimens as tows were prepared for tensile testing with the use of ASTM-D-4018 standard [23]. According to the standard, the length of the specimens is 150 mm and the test speed is 5 mm/s. The mechanical

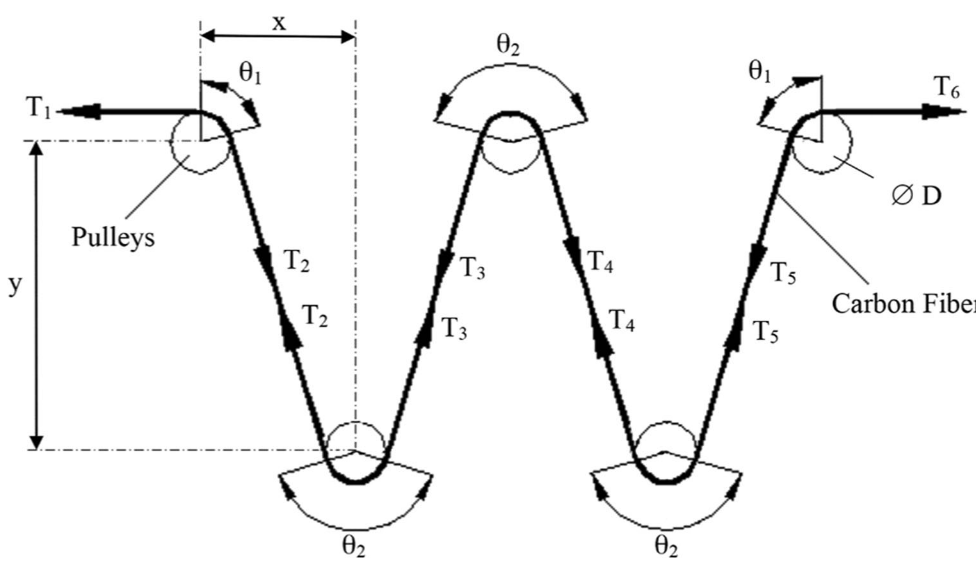

Fig. 2 Modeling of tension forces and contact angles

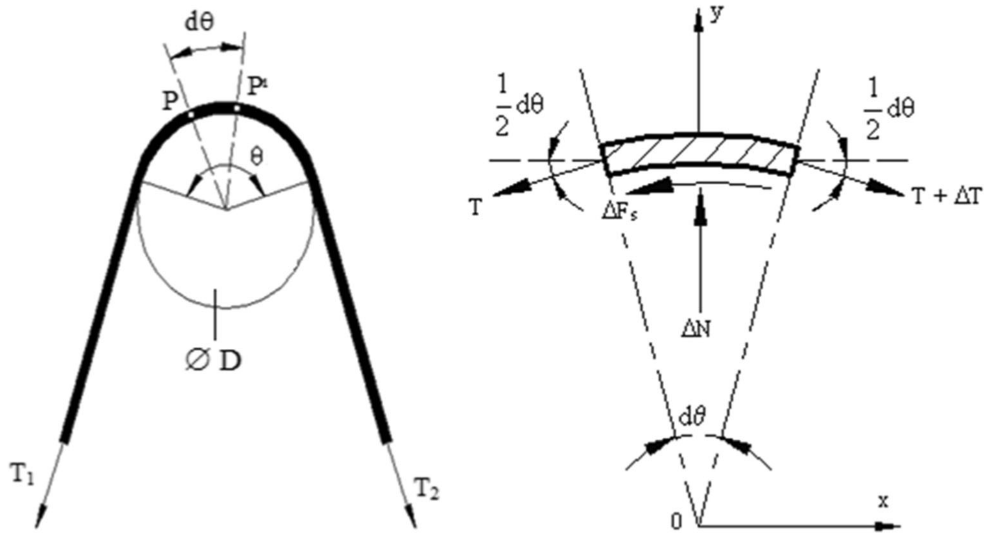

Fig. 3 The details of the contact angle and forces on a single pulley

properties of these specimens are shown in Table 2. In all the experiments, continuous carbon fiber, one of the products of Toray Company known as T700SC-12000, was used.

The tensile strength of the carbon fiber was measured by tensile testing experiments to identify how the mechanical properties of carbon fiber were affected during the winding process. During the filament winding process, carbon fiber passes through the pretensioning unit under dry conditions. This being the case, the experiment was carried out without resin bath.

4 Results and discussion

High-strength composite structure parts are mostly manufactured by a FW method using continuous fiber. Some discrepancies between theoretical calculation and experimental results were observed in the previous studies while predicting the real strength of composite structures manufactured by FW design.

Mertiny and Ellyin [1] studied the effect of pretensioning on the loss of strength in filament winding cylinders. But they left out of their experiments and findings what occurs between fiber and pulleys when the force of pretensioning was increased or reduced. The angle of fiber passing through the tension unit pulley is also a very important parameter since it causes bending stress and then length contact in fibers.

Carbon fiber tows pass through the pretensioning unit under dry condition but the same tows of CF were implanted in the resin to form a final geometry in the winding machine after the pretension unit. This is why the experiment, in order to understand the effect of pretension force, was executed in the dry condition of CF. First, the pretension force is kept constant and the diameter and positions of pulleys were changed to understand the effect of the entrance angle and contact length on carbon fiber damage.

Table 1 Winding conditions used to determinate damage of carbon fiber

Test no.	x (mm)	y (mm)	Total contact angle ($\sum\theta$) (Rad)	Diameter of pulleys ($\varnothing D$) (mm)	Roving tension (T) (N)
Test 0	Undamaged				
Test 1	200	400	10.28	78	19.62
Test 2	200	400	9.43	32	19.62
Test 3	200	400	10.28	78	24.52
Test 4	200	400	9.43	32	24.52
Test 5	200	780	11.34	78	19.62
Test 6	200	780	10.88	32	19.62
Test 7	200	780	11.34	78	24.52
Test 8	200	780	10.88	32	24.52

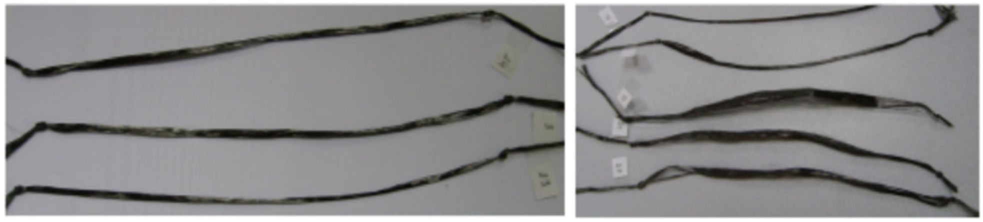

Fig. 4 The tensile specimens of dry carbon fiber after winding [23]

Friction force is one of the main factors leading to damage of the fiber as it passes through the pretension unit. Equation 3 was used to calculate the pulling and pretension forces which were created by friction forces in the pretension unit. In this equation, T_1 was assumed constant according to the winding conditions as seen in Fig. 3. T_6 force was calculated using Eq. 3 for different contact angles which are obtained from different winding conditions. The variation of the tension force T_6 which is obtained from Eq. 3 is plotted in Fig. 5 under different testing conditions. This figure reveals that the pulley diameter has an important effect in defining pretension force. The pulley diameters were 78 mm on test 1 and 32 mm on test 2. An increase in the pulley diameter results in an increase in the pretension force. Although the other parameters are constant, a similar increase in tension force caused by larger pulley diameters is also observed in the comparison between test 3 and test 4, test 5 and test 6, and test 7 and test 8. A larger contact angle may be the factor behind this increase. It can be seen from the same figure that a decrease in the pulley diameters results in reduce contact angle and less contact length leads to reduced T_6 forces.

Figure 6 indicates the fiber strength loss of various carbon fibers processed according to a different pulley diameter and pretension force. The same figure shows that when the pretension force is adjusted to a constant value of 19.62 N during the winding process and the total contact angle (Rad) is changed (by changing the position and diameter of the pulleys) to 11.34, 10.88, 9.43, and 10.28, the tensile strength of CF is reduced by 30, 35, 14, and 10%, respectively.

The loss of fiber strength due to winding conditions clearly demonstrates that an increase in both the pretension and total contact angle also increases damage as shown in Fig. 6. The pretension force was also increased to 24.52 N to observe what happens when the force is increased. The results of the tensile strength of fibers are given in Fig. 6 under the increased tensioning force of 24.52 N. Again, the pulley entrance angles of fiber into the pulley are adjusted to 11.34, 10.88, 9.43, and 10.28, and the tensile strengths of CF are reduced by 39, 43, 23, and 18%, respectively.

These two figures clearly demonstrate that the friction angle and the friction force have an impact on fiber strength.

Additionally, these two figures illustrate that if the pretension force during the winding process is increased, the tensile strength of carbon fiber decreases. The reason for this decrease might be due to accumulated damage to the fibers when the bundle of fiber went through the pulleys of the tensioner. For the strength of material, it is clear that bending stress combined with high tension in fiber may result in greater damage.

The pulley diameter and the position of the pulley are the main decisive parameters affecting tensioning unit damage. These parameters affect the angle of the fiber passing through the pulleys. The damage caused by different pretension forces is shown in Fig. 7. Tensile strength of the carbon fiber is reduced from 10 to 39% when the diameter of the pulleys is kept at a constant value of 78 mm (Fig. 6). The same situation is seen with pulleys whose diameter is 32 mm. The values for small-diameter pulleys range from 14 to 43%. The comparison of the effect of the small-diameter pulley to that of the larger diameter pulley indicates that the damage proceeding from the small-diameter pulley is greater.

Figure 7 shows the tensile strength of non-damaged fiber (as obtained from the manufacturer) with no pretensioning in comparison with damaged carbon fiber. This figure indicates that the smaller the pulley diameter, the greater the bending stress caused by pretension force in fibers. In addition to the bending stress in the tow, the degree of the bundle angle adds

Table 2 Mechanical properties of dry continuous carbon fiber (T700SC-12000) specimens

Cross-sectional area (A) (mm^2) (average)	Number of filament	Diameter of single filament (mm)	Young's moduli (E) (GPa)	Tensile strength (MPa)	Poisson ratio (υ)	Shear moduli (G) (GPa)	Density (ρ) (g/cm^3)
0.46	12,000	0.007	230	4900	0.19	96.6	1.8

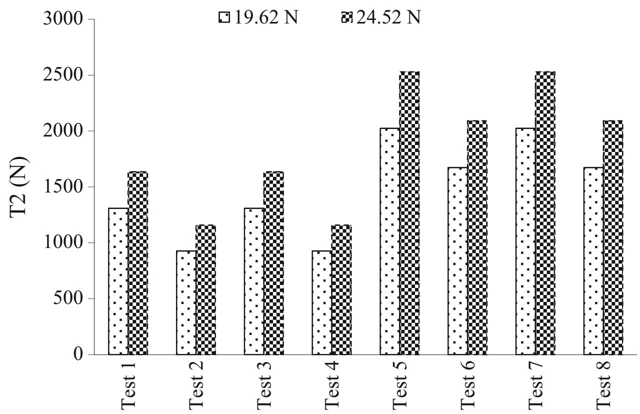

Fig. 5 Variation of T_2 forces for different test conditions

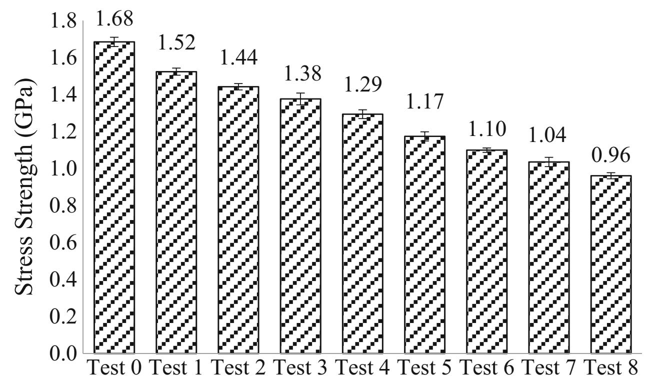

Fig. 7 Comparison of the results of the tensile strength for all winding conditions.

further bending stress to a single bundle while moving through the pulley. Figure 7 also indicates that an increase along the *y*-axis (vertical distance between pulleys) results in more damage to the fibers. A change along the *y*-axis from 400 to 780 mm causes a change in the bundle contact angle (Rad) from 10.28 to 11.34.

Friction is the main reason for the fiber damage in the tension unit. Normal force to the pulley, which is a function of tension force, generates friction. Increased tension force may result in increased friction force thus causing more damage to the fibers. Furthermore, increased tension causes greater bending stress when the fibers are randomly placed next to each other. Considering that the diameter of the carbon fiber is around 7 to 10 μm and that its structure is brittle, it is very easy for some of the fibers to break during their fast movement through the pulleys. The broken fibers may in turn serve as an obstacle to unbroken fibers which leads to an increase in the number of broken fibers. As shown in Fig. 7, when the pulley used has a diameter of 78 mm and the pretension force is adjusted to 19.62 and 24.52 N, the tensile strength of dry carbon fiber is reduced by 10–39% during the winding process on the pretensioning unit.

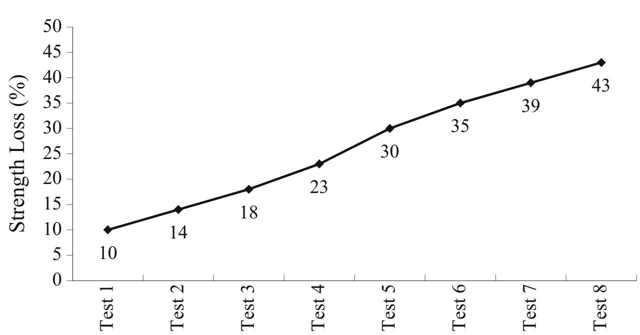

Fig. 6 The strength loss dependency on winding conditions

5 Conclusion

The effect of the pretension force on the strength of continuous carbon fiber in FW process was the focus of investigation in the present study. A winding system has been developed to simulate the process to understand the effects of the parameters such as roving tension, pulley diameter, and contact angle between pulley and fiber. The following conclusions have been observed from the present investigation:

1. Experimental results indicate that the tensile strength of carbon fiber is reduced by 10–43% depending on the pretensioning unit parameters such as roller diameter, fiber feeding angle, and tensioning force on the fiber.
2. The damage to the carbon fiber increases, as the total contact angle ($\sum\theta$) increases, because of increased friction forces between roller and fiber.
3. The damage to the carbon fiber increases as the pretension force on the carbon fiber during the winding process increases. Higher tension force on the fiber results higher breakage and neps.
4. Experimental results showed that the smaller the diameter of the pulleys used in the pretensioning unit, the greater the damage to the carbon fiber because of the effects of increased bending on the fiber.

Notation

T_1	Pretension force
T_2	Pulling force
μ	Friction coefficient
$\sum\theta$	Total contact angle

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