Development of a tension system and influence of ultimate tension on the properties of composites

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Abstract. The demand for high tension winding has increased in recently years. However, in-depth studies on high- tension winding have not been conducted. In the current study, a device was developed to apply tension to the winding process, and several fibers were adopted. A new method of tension controlling tension was applied in the experiments, allowing accurate and digital control of tension in the winding. Ultimate tension (pretension) in filament winding process was evaluated. Samples with varying tension were selected for the experiment and their physical and mechanical properties were measured. Experimental results indicated that tension in winding significantly affect composites. The function of the tension was subsequently analyzed. This study concluded that the ultimate pretension in winding was far less than the fracture tension, ultimately influencing the physical and mechanical properties of composites.

1. Introduction
High-speed composite rotors, composite tubes and pressure vessels are typically manufactured by filament winding [1–3]. In filament winding, winding tension (pretension) is considered a vital parameter to measure the performance of a product [4, 5]. A numerical control method was applied in a winding tension system to achieve accurate and real-time tension adjustment [6–11]. Currently, tension on the filament can be controlled using two methods. One method is with the use of a tensioner connected to the fiber package on a card or metal tube. The tensioner in a tension control system could be a magnetic brake, torque motor, or servo-motor [6–8]. The other method is with the use of a drag wheel, which is connected to the magnetic brake or torque motor, when the filament winds through it [9]. High pretension can be required in a composite product, such as, a high-speed PM rotor composite sleeve and a composite flywheel [1]. However, high-tension winding for the current winding machine is difficult to obtain. In summary, studies are rarely been reported on high-tension winding and the development of a pretension control system that could supply sufficient tension for filament winding. In addition, studies on the maximum allowable tension in filament winding are rarely conducted.

In the present study, a new tension control system for filament winding was developed. This new device does not only apply sufficient pretension on the filament; it is also low-cost and has a less occupied area. In the test, the device used in filament winding and carbon fiber (CF), Kevlar fiber, and polybenzoxazole (PBO) fiber were adopted. Meanwhile, the maximum allowable tension of these fibers in winding was tested. The properties of the composites with varying tension were then characterized. Research shows that the developed tension control system can effectively apply high tension on filaments, and a significant difference in the properties of the composites with varying tension is indicated.
2. Experimental

2.1 Method and Device

The method used to apply tension is similar to the second method [9] mentioned earlier, which produces static friction resistance through the tensioner during filament delivery. This numerical tension control system mainly consists of a tension meter, a tension actuator and a controller. The tension actuator is mainly composed of two magnetic powder brakes, two roll shafts, and a shell frame. The controller can automatically adjust the excitation current of the magnetic powder brake according to the set target tension and the measured tension after PID (proportional-integral-derivative) operation. The two roller shafts are connected to a magnetic powder brake. The axes of the two roller shafts form an angle between them. The schematic of the tension control system is presented in Figure 1, and an image of the system is shown in Figure 2. The first roller shaft is connected to the second magnetic powder brake, which slants the second roller shaft. The axis of the second roller shaft is perpendicular to the line of the filament on the surface of the shaft. The second roller shaft is connected to the first magnetic powder brake. After the filament is dispensed from the fiber package, the filament should be wound from the large opening end formed by two shafts. The principle of tension application is that the tension is obtained by static friction generated from filament winding on the surface of two roller shafts. The schematic of the control principle of the tension system is shown in Figure 3. This device can produce greater tension than the single drag wheel device. The filament was then delivered to the tension meter. The tension detection mechanism consists of six guide wheels and a torque arm.

![Schematic of the tension control system](image1)

**Figure 1.** Schematic of the tension control system:(a) top view; (b) side view, (1) filament, (2) first roller shaft, (3) first magnetic powder brake, (4) tensionmeter, (5) the second roller shaft, (6) second magnetic powder brake.

![Photograph of the system](image2)

**Figure 2.** Photograph of the system: (a) general view, (b) local view.
The torque sensor passes the measured value to the controller after the transmitter conversion. The digital controller acts a closed-loop feedback control. The PID control algorithm was adopted in the experiment. The operator can digitally input tension and select the tension control mode. Winding is completed automatically, and the parameters can be digitally displayed and controlled. Therefore, the tension can be controlled accurately and digitally in tape winding.

### 2.2 Materials

High-strength fibers, such as carbon, Kevlar, and S-glass are usually chosen as materials for winding composites, and wet winding is the commonly used and suitable method. Compared with Kevlar fiber, PBO has a higher strength and a higher modulus. In the current study, CF, Kevlar and PBO were used. Kevlar was provided by DuPont Co. and of type K29 with a linear density 1670 dtex. The PBO (Zylon HM) was supplied by Toyobo Co., with a linear density is 1670 dtex. The properties of the fibers and the normal winding tension are listed in Table 1. A heat-resistant epoxy resin was selected as the matrix of the composites. The properties of the resin are listed in Table 2.

#### Table 1. Properties of the fibers and winding tensions.

| Fiber type | Number of filament | Tensile strength (MPa) | Tensile modulus (GPa) | Tow cross-sectional area (mm²) | Winding tension (N) |
|------------|--------------------|------------------------|-----------------------|--------------------------------|---------------------|
| T700S      | 12K                | 4900                   | 230                   | 0.444                          | 32→30→28→26        |
| T800H      | 12K                | 5490                   | 294                   | 0.245                          | 22→20→18→16        |
| T1000G     | 12K                | 6370                   | 294                   | 0.269                          | 26→24→22→20        |
| M40J       | 6K                 | 4410                   | 377                   | 0.127                          | 15→14→13→12        |
| M50J       | 6K                 | 4120                   | 475                   | 0.116                          | 15→14→13→12        |
| T700S      | 12K                | 4900                   | 230                   | 0.444                          | 35→33→31→29        |
| towpreg    |                    |                        |                       |                                |                     |
| Kevlar     | –                  | 3600                   | 83                    | 0.116                          | 15→14→13→12        |
| PBO        | –                  | 5800                   | 270                   | 0.105                          | 15→14→13→12        |
Table 2. Properties of the resin.

| Property          | Value | Density (g/cm³) | Tg (°C) | Tensile strength (MPa) | Tensile modulus (GPa) | Elongation at break (%) | Flexural strength (MPa) | Flexural modulus (GPa) |
|-------------------|-------|-----------------|---------|------------------------|----------------------|------------------------|------------------------|------------------------|
|                   |       | 1.21            | 205     | 70                     | 2.3                  | 3.6                    | 120                    | 2.5                    |

2.3 Ultimate Tension of Filament Testing
Breakage and damage in the fiber bundles were inevitable in high-tension winding. Larger damage and breakage in fiber bundles indicated difficulty in winding and a decrease in product strength. Therefore, the maximum pretension of the filament in winding process should be evaluated. In the tension control system, the applied tension increased gradually until the filament was destroyed. Ultimate tension was measured, and ultimate tensile stress was calculated based on the basic parameters of the fiber.

2.4 Winding with Different Pretensions

2.4.1 Physical Property Testing
The density of the composites with different winding tensions was measured with a density meter. The fiber volume fraction and porosity of the composite specimen were measured with the microscope method based on the Chinese standard GB/T3366.

2.4.2 Mechanical Property Testing
In accordance with the ASTM: D2290-12, the hoop tensile strength of the winding composite was measured. These tests were carried out on a mechanical test machine (CTM Co., 10T) using a cross-head displacement rate of 1.3 mm/min. The procedure of inter-laminar shear strength (ILSS) is outlined amply in ASTM: D2344-16. The lengths of the samples cut from rings were six times the thickness, and the widths of arcs measured 10mm. The test were carried out on the testing machine (CTM Co., 500Kg) with a crosshead displacement rate of 1mm/min.

3. Results and Discussion

3.1 Ultimate Tension in Winding Process
Figure 4(a) shows that CFs in wet winding have lower ultimate tension compared with towpreg, Kevlar, and PBO. In these CFs, the T700 12K type exhibits the highest ultimate tension, whereas the M50 6K type exhibits the lowest tension. The fibers are likely to break when the filament passes through the guide pulley in winding because CFs are more brittle than organic fiber. The towpreg has a high ultimate tension because of the resin. The resin protects the fiber from damage during fiber delivery and transfers stress between the fibers while filaments in a bundle of fibers cannot be uniformly stressed at a loading state. Ultimate tensile stress is the ratio of ultimate tension to the cross section of the fiber bundle. As presented in Figure 4(b), ultimate tensile stress is higher in Kevlar and PBO than in CFs. The ultimate tensile stress of T700 towpreg was not higher than that of CFs in wet winding.
3.2 Physical Property

The fiber volume fraction, density, and porosity of composites with ultimate tension (UT) and normal tension (NT) are listed in Table 3. The table shows a clear trend of increasing fiber content and density with ultimate tension. Delamination and lack of resin could be observed in the Kevlar and PBO composites with ultimate tension. Thus, density, fiber content, and porosity were difficult to measure accurately. The porosity of CF composite decreased when ultimate tension was applied.

Table 3. Physical property of composites.

| Fiber type     | T700 | T800 | T1000 | M40  | M50  | T700 towpreg | Kevlar | PBO |
|----------------|------|------|-------|------|------|--------------|--------|-----|
| Density (g/cm³) NT | 1.561| 1.602| 1.553 | 1.60 | 1.62 | 1.5          | 1.356  | 1.43|
|                 UT | 1.593| 1.613| 1.601 | 1.62 | 1.64 | 1.515        | -      | 3   |
| Fiber content (%) NT | 64.6 | 62.8 | 63.1 | 63.2 | 63.7 | 61.8         | 65.3   | 64.9|
|                 UT | 69.7 | 66.4 | 70.3 | 68.4 | 69.5 | 64.5         | -      | -   |
| Porosity (%) NT | 2.8  | 2.4  | 2.2  | 2.3  | 2.0  | 3.7          | -      | -   |
|                 UT | 2.3  | 2.1  | 2.0  | 2.1  | 1.9  | 3.2          | -      | -   |

3.3 Mechanical Property

As shown in Figure 5(a) (b), the tensile strength and inter-laminar shear strength (ILSS) of the CF composite in wet winding decreased with ultimate tension. The range of decline in the hoop tensile strength of the samples was lower than that of the ILSS. In Figure 5(b), the ILSS of values of the high-modulus fibers M40 and M50 are higher than those of high-strength fibers. For the T700 towpreg, the ILSS of the samples with ultimate tension was higher than that with normal tension, which varied from the others because the viscosity of resin in towpreg winding was higher than that in wet winding. Thus, excess resin cannot be easily extruded for normal tension. Under the influence of ultimate tension, the resin content can reach the optimal proportion. In addition, the porosity of the towpreg composite decreases with an increase in tension, which significantly affects ILSS. As shown in Figure 5(c), the tensile strengths of the Kevlar and PBO composites increase rather than decrease with ultimate tension. For CF, the damage of the fibers and the inadequacy of the resin content lead to a low mechanical strength in the composite when ultimate tension was applied. Although the ILSS of Kevlar and PBO composite was close to zero, reduced lower resin content did not decrease the tensile strength of the composite. Owing to the superior toughness of organic fibers, considerably few fibers were damaged and broken during the filament delivery.

Figure 4. Ultimate tensile property of the filament: (a) ultimate tension of fibers, (b) ultimate tensile stress of fibers.
Figure 5. Mechanical strength of composites: (a) tensile strength of CF composites, (b) ILSS of CF composites, (c) tensile strength of towpreg and organic fiber composites, (d) ILSS of towpreg and organic fiber composites.

4. Conclusions
In this study, a new method of tension control was adopted, and a related device was developed. The developed device was proven capable of applying specific winding tension. Both method and device were used in filament winding, and ultimate tension testing of filament was conducted using the developed device. The results indicate that the ultimate tensile stress of fiber is far less than the strength of the fiber. Kevlar, PBO, and T700 towpreg can exert high ultimate tension. The Kevlar fiber and PBO can achieve a high ultimate tensile stress. M40 and M50 have higher ultimate tensile stress than do other CFs. The ultimate tensile force can reduce the porosity, as well as increase the density and fiber content of the material. The ultimate tension can significantly affect the mechanical properties of wound composite. The tensile strength of the CF composite is decreased with ultimate tension, whereas the tensile strengths of Kevlar and PBO are increased. The shear strengths of most of composites decreases, except that for the T700 towpreg.

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