Size Effect on the Mechanical Properties of CF Winding Composite

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Abstract. Mechanical properties of filament winding composites are usually tested by NOL ring samples. Few people have studied the size effect of winding composite samples on the testing result of mechanical property. In this research, winding composite thickness, diameter, and geometry of NOL ring samples were prepared to investigate the size effect on the mechanical strength of carbon fiber (CF) winding composite. The CF T700, T1000, M40, and M50 were adopted for the winding composite, while the matrix was epoxy resin. Test results show that the tensile strength and ILSS of composites decreases monotonically with an increase of thickness from 1 mm to 4 mm. The mechanical strength of composite samples increases monotonically with the increase in diameter from 100 mm to 189 mm. The mechanical strength of composite samples with two flat sides are higher than those of cyclic annular samples.

1. Introduction

The filament winding composite can be used in cylinders, pipes, the flywheel, and rotor sleeve [1–3]. A NOL ring specimen was recommended to evaluate the properties of annular composite, which refers to standard ASTM D2290 and ASTM D2344 [4]. However, the size of composite products differs from that in standard, which includes the thickness and diameter of the winding composite. In addition, the split-disk method introduces a bending moment in the sample when tensile testing, causing the tensile strength of test results to be relatively low [5]. Although the tensile property obtained by the pressure blasting method is the more accurate than that obtained by the split-disk method, the latter has the advantages of being low cost and simple [6]. El-Bagory conducted a series experiment to investigate the effect of specimen geometry and speed on the predicted mechanical behavior of polyethylene pipe material. In addition, notched ring specimen and full ring specimens with different fixture types indicate different strength and strain value [7]. Kaynak C concluded that split-disk tests are an effective method to determine hoop tensile properties of filament-wound tubular structures [8]. Carbon fiber and glass fiber were selected as fiber materials in his research, and tests with carbon fiber reinforced specimens resulted in relatively higher deviations. Ghasemi A. R. considered the behavior of carbon/epoxy NOL-ring composite materials with varying hole diameter subjected to thermal cycling loading [9]. The results indicated that holes in specimens cause significant stress concentration and mechanical property instability in comparison with thermal cycling effects.
Few people have studied the size effect of winding composite samples on the testing result. The effect of thickness, diameter, and geometry of NOL rings on the testing results of mechanical properties was not deeply studied. In addition, the split-disk method that has no bending moment was rarely used to evaluate the strength of the composite material. Thus, few people made a comparative analyses on two kinds of testing methods.

In the present study, a series of experiments were conducted to investigate to size effect of winding composite on the testing results of mechanical properties. The mechanical properties of samples with varying thickness, diameter, and distinctive split-disc geometry were measured. The mechanical properties include tensile strength and inter-laminar shear strength (ILSS). CF T700, T1000, M40, and M50 were used as reinforced fiber in the filament winding composite. Research shows that varying thickness, diameter, and split-disc geometry significantly affect the testing result of mechanical properties.

2. Experiment

2.1. Material
Carbon fibers are usually chosen as materials for winding composites on account of their high strength and high modulus, and wet winding is the most suitable and commonly used method. Toray T700 and T1000 are among the typical products of high-strength CF; M40 and M50 have high moduli.

2.2. Resin and process
A 4-axes numerical controlled winding machine (Shanghai Vanguard Co., VG4FW) was used for filament winding process. Winding was carried out at the 25°C, and indoor relative humidity was maintained at 40%–50%. The properties of the CF (Toray Co.), process parameters 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.

| 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                | 35                            |
| T1000G 12K | 6370               | 294                    | 0.269                | 25                            |
| M40J 6K   | 4410               | 377                    | 0.127                | 10                            |
| M50J 6K   | 4120               | 475                    | 0.116                | 10                            |

Table 2. Physical and mechanical properties of resin.

| Property                  | Density (g/cm³) | Tg (°C) | Tensile strength (MPa) | Tensile modulus (GPa) | Elongation at break (%) | Flexural strength (MPa) | Flexural modulus (GPa) |
|---------------------------|-----------------|---------|------------------------|-----------------------|-------------------------|-------------------------|------------------------|
| Value                     | 1.21            | 200     | 68                     | 2.2                   | 3.3                     | 115                     | 2.4                    |

2.3. Method
A number of NOL ring samples were prepared to investigate the size effect on the testing results of winding composite. The internal diameter of the samples is 100mm and the thickness are 1 mm, 2 mm, 3 mm and 4 mm, respectively. For the experiments of samples with varying diameters, the internal diameter of the samples is 100 mm, 122 mm, 142 mm, 161mm, and 189mm, respectively, and with all of the thickness of samples being 3mm. The NOL ring samples and the split-disk tensile fixture with varying size and geometry were shown in Figure 1. As shown in Figure 1(b), the split-disks have two flat sides, which produce no bending moment to NOL ring samples during the tensile process.
2.4. Mechanical property test
In accordance with the ASTM: D2290-12, the hoop tensile strength of the winding composite was measured. As the size of winding samples varied from that of the standard, tensile test fixtures were made to suit the size of current composites. 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 ILSS is one of the basic mechanical properties of composites and can be characterized by the short beam shear strength method. The procedure is outlined amply in ASTM: D2344-16. The lengths of the samples cut from rings were six times the thickness, and the widths of the arcs measured 10mm. The tests were conducted on a testing machine (CTM Co., 500kg) with a crosshead displacement rate of 1mm/min. The loading nose had a hardness of 60HRC and a radius of 3mm. The testing fixture and samples are shown in Figure 2. Not only were the samples with varying thickness and size made, but a batch of composite samples were also prepared with the mandrel that has two flat sides. The site of arc notch is in the flat sides of the samples for the tensile strength testing. Some straight strips were cut from the composite samples with two flat sides, which were applied to ILSS testing.

3. Result and discussion

3.1. Mechanical properties of composite with varying thickness
As shown in Figure 3, the tensile strength and IL shear strength of each composite samples decreased with an increase in thickness. The tensile strength of T700 samples with a thickness of 4mm was 1552MPa, which decreased by 41% compared with the samples with a thickness of 4mm. For the T1000 composite, the tensile strength decrease by 24%, while the thickness increased from 1mm to
4mm. The variation range of tensile strength of the T700 composite was higher than that of the T1000 composite. The decreasing degree of ILSS of the T700 and T1000 were 33% and 24%, respectively. The variation range of ILSS of the T700 was lower than that of tensile strength, and the ILSS of the T1000 sample has the same decreasing degree as the tensile strength. The mechanical strength trend of high modulus CF M40 and M50 is the same as high strength CF T700 and T1000, which decreases monotonically with an increase in thickness. However, although the M40 composite has high tensile strength, the variation range of tensile strength of M50 composite was higher than that of M40. In addition, the decreasing degree of ILSS of M40 was higher than that of M50, which was 35% and 24%, respectively.

![Figure 3](image1)

**Figure 3.** Mechanical strength of composite with varying thickness: (a)T700, (b)T1000, (c)M40, (d)M50.

3.2. Mechanical properties of samples with varying diameter

As shown in Figure 4, the tensile strength and ILSS of these CF samples increase monotonously with an increase in sample diameter. Obtained by the 189mm T1000 composite, the measured mechanical strength maximum of annular samples was 2755 MPa, and 95 MPa, respectively. The M50 and M40 composite in the size 100mm exhibited the lowest tensile strength and ILSS, namely 1170 MPa and 47.55MPa, respectively. The tensile strength of the T700 composite increased by 19% when the diameter increased from 100 mm to 189 mm. For the T1000 composite, the tensile strength increased by 14% with the diameter increase from 100 mm to 189 mm. The increasing degree of tensile strength of M40 composite with the diameter increase from 100mm to 189mm is the same as that of M50 composite, which is approximately 15%. It can evidently be seen that the increasing degree of ILSS of the samples are higher than those of tensile strength. Compared with samples having a 100mm diameter, both the ILSS of T700 and T1000 composites having a 189mm diameter increased by 61%.
For the M40 composite, the ILSS increased by 49% with the diameter increase from 100 mm to 189 mm, whereas the ILSS of M50 samples increased by 33% with the diameter increase. In general, the mechanical strength of high-strength CF exhibited a higher variation range than that of high-modulus CF with an increasing diameter.

It is common knowledge that the split-disk could produce a moment to the sample during the NOL ring tensile process. The smaller the diameter of the NOL ring, the more obvious the effect of this bending moment. It can be considered that the measured tensile strength of samples with the 189 mm diameter is closer to real tensile strength of samples with the 100 mm diameter. Moreover, the internal stress that includes radial and hoop stress in samples is unavoidable, resulting from the filament winding and resin curing process [10]. Generally, the internal stress of large diameter circular composites is lower than that of small diameter circular composites. Thus, the tensile strength of these CF samples increase monotonously with an increase in sample diameter. For the ILSS, the resin matrix plays a dominant role, and samples having large curvatures are prone to having uneven distributions of stress, weakening the ILSS. Thus, the ILSS of samples exhibit the same trend as the tensile strength. The strength of the resin matrix is much lower than the strength of the carbon fiber, resulting in a higher variation range of ILSS compared with the tensile strength.

3.3. Mechanical properties of samples with different geometry

As shown in Figure 5, the mechanical properties of composite samples with two flat sides are higher than those of cyclic annular samples. It can be argued that the measured tensile strength of the composite samples with two flat sides are not affected by bending moments. In addition, the
composite samples with this geometry have no internal stress induced by the filament winding process. The measured result of composite obtained with this geometry could reflect the real properties of the winding composite.

![Composite samples with two flat sides](image)

**Figure 5.** Mechanical strength of composite samples with two flat sides

### 4. Conclusion

In this study, the mechanical strength of winding CF/epoxy composites with varying thickness, size and geometry were evaluated. The CFs employed included T700, T1000, M40, and M50 with the heat-resistant epoxy resin being most suitable for the filament winding process. Although the same tension is used for the same kind of fiber, the thickness, size, and geometry of the sample are varied. The results show that the tensile strength and ILSS of composites decrease monotonically with an increase in thickness. The variation range of the tensile strength and ILSS are similar. The tensile strength and ILSS of composite samples increases monotonically with the increase in diameter. The variation range of the tensile strength of composite is lower than that of ILSS. In addition, the mechanical strength of high-strength CF exhibit a higher variation range than that of high-modulus CF with an increasing diameter. The mechanical properties of composite samples with two flat sides are higher than those of cyclic annular samples.

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