Enhancing Longitudinal Compressive Properties of Unidirectional FRP Based on Microbuckling Compression Failure Mechanism

Fangtao Ruan, Zhenzhen Xu, Dayin Hou, Yang Li, Changliu Chu

Anhui Polytechnic University, School of Textile and Garment, Wuhu CHINA

Correspondence to:
Fangtao Ruan email: rft62@sina.com

ABSTRACT

In this study, a new methodology to improve the longitudinal compressive strength and modulus of ultra-high molecular weight polyethylene (UHMWPE) fiber-reinforced epoxy resin matrix is developed. The proposed method involves wrapping a UHMWPE fiber bundle with a poly-p-phenylene benzobisoxazole fiber filament using a winding method, and using these bundles to fabricate unidirectional UHMWPE fabric. UHMWPE/epoxy composites were fabricated using vacuum-assisted resin-transfer molding (VARTM), and the compression properties of the composite were evaluated and compared to investigate the effect of the filament wrapping. Improvements in the compressive modulus were achieved for filaments wound with applied tension, and when increasing the filament-winding spacing; however, the compressive strength decreased with an increase in the filament-winding spacing. Results obtained confirm that fiber microbuckling failure occurred in the composite under longitudinal compression, and that inhibiting the buckling length of the fiber improved compressive properties. These results may be useful when designing the mechanical properties of fiber-reinforced polymer composites.

Keywords: Unidirectional FRP; longitudinal compression; micro-buckling failure; filament wrapping

INTRODUCTION

Fiber-reinforced polymer (FRP) composite materials are formed of a resin matrix containing fibers with high strength and high modulus, both of which play an important role in determining the mechanical properties, as the resin matrix fixes those fibers and transfers the loads. Continuous fiber-reinforced resin composite materials have advantages of high specific strength and specific modulus, and good fatigue resistance. These structural properties have led to FRPs being extensively researched, and they are widely used in aerospace, automobiles, ships, construction, and other fields [1, 2]. An FRP has anisotropic mechanical properties owing to the orientation arrangement structure of the fibers in FRP. The compressive properties of FRPs are generally lower than the tensile properties, e.g., the compressive strength usually ranges between several tens to hundreds of MPa, which is 50–60% of their tensile strength [3, 4]. The ratio of the tensile strength to the compressive strength of aramid fiber-reinforced composite is 0.15. Although the material has the advantage of good tensile strength, it has difficulty to withstanding compression loads, which limits the application of aramid fiber in FRPs. Furthermore, the flexural performance of FRPs also depends on the compressive properties. S. L. Bazhenov [5, 6] reported that the flexural failure of unidirectional aramid fiber-reinforced epoxy composites originated near the compression surface, and the final stage of the failure process is a fracture of fibers near the opposite tensile surface of the specimen; thus, the compressive property is also an important factor that affects the flexural resistance. This weakness in compression severely limits the structural efficiency of FRPs. With the rapidly increasing use of FRPs for compressive load-bearing applications [7, 8], such as bridge engineering and deep-diving devices, it is necessary to realize improvements and to understand the principles of compressive failure. To obtain better compressive performance, researchers have optimized the design of FRPs using methods such as resin or fiber-surface modification, as well as the hybridization and novel weaving of reinforced fibers. Arun K. Subramaniyan [9] reported that the longitudinal compressive strengths of glass fiber-reinforced composites extracted from off-axis tests show increases of 22%

and 36% with 3% and 5% nanoclay loading, respectively. Tao Yang et al. [10] decorated polyimide (PI) fibers with carbon nanotubes, and investigated its use for the reinforcement of phosphoric-acid-based geo-polymers. Compared to undecorated geopolymers, the composites achieved a 120% increase in the compressive strength. Martyn Hucker [11] proposed that hollow glass fiber weight fractions around 20–25% may offer significantly improve the specific compressive strength as against the use of non-hollow fibers. These methods do not significantly improve the effect, but the cost and weight are increased, which counter the lightweight advantages of FRP materials. In recent years, three-dimensional (3D) braided FRP has been extensively considered for its high compression performance [12-14]. The compressive properties of 3D four-directional braided composites were studied [15], and it was found that the braiding angle significantly affects the compressive properties and compression failure mechanism. The influence of the change in the yarn structure on the compressive properties and failure mechanism of 3D braided composites was studied by Shivakumar [16], and it was found that the arrangement of axial yarns has a greater influence on the compressive strength than the axial yarns. However, the 3D braided composite improves the compression performance at the expense of the bias in the direction of the yarn tensile properties. No axial yarn occupies the residual braided voids; thus, the effective fiber volume fraction (FVF) is decreased, which limits the compression performance of 3D braided composites. There are many opinions about the compressive failure mechanism of FRP. In general, studies on this topic are divided into two branches: fiber micro-buckling models and kink band formation models. Rosen [17] reported that there are two types of microbuckling in unidirectional FRP under compression, namely an extensional mode and a shear mode, In composites with a significant FVF, i.e., $V_f > 0.3$, the shear mode governs the compressive failure. For a low FVF or ductile fiber-reinforced composite, the extensional mode will occur. Although there are many factors that affect their compression properties, the limitations of fiber microbuckling are important. In this paper, the concept of filament-wrapped fiber-bundle-reinforced unidirectional composites is proposed, which is a novel and simple braid method. The promotion mechanism is based on the microbuckling compression failure mechanism. The fiber buckling process of filament-wrapped fiber-bundle-reinforced plastic and normal fiber-reinforced plastic are shown in *Figure 1*. In general, the Young's modulus of the reinforced fiber is much larger than that of the resin matrix; therefore, the effect of the surrounding matrix was omitted in this study. The Euler buckling theory for cylindrical objects was used to analyze the enhancement in the longitudinal compressive properties of unidirectional fiber composites, and the formula is given in Eq. (1).

$$P_{cr} = \frac{\lambda \pi^2 \mathrm{EI}}{l^2} \tag{1}$$

P_{cr}: compressive buckling critical load;
EI: moment of inertia of fiber;
l: buckling critical wavelength

To improve the compressive buckling critical load of FRP, the fiber buckling is prevented by shortening the buckling critical wavelength. According to the Euler formula, a shorter l may improve P_{cr} when the fibers are under compression. The critical buckling stress of the longitudinal compressive unidirectional FRP may be improved. As shown in *Figure 2*, the filament-wrapping process in the hoop direction would shorten l owing to the restriction of F_2, which is offered by the filament wrapping.

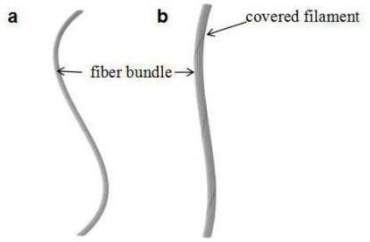

FIGURE 1. Model of (a) normal fiber bundle and (b) filament-wrapped fiber bundle.

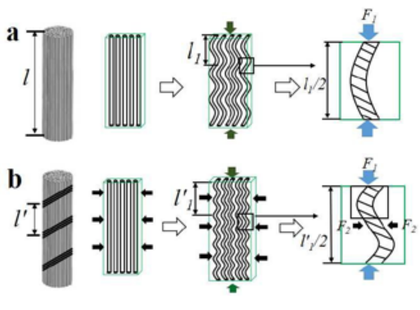

FIGURE 2. Simple model for fiber buckling process during compression: (a) normal fiber-bundle-reinforced plastic; (b) filament-wrapped fiber bundle reinforced plastic.

EXPERIMENTAL

Materials and Processing

The ultra-high molecular weight polyethylene (UHMWPE) fiber utilized was Dyneema SK60 (Toyobo, Japan). The wrapping filament was poly-p-phenylene benzobisoxazole (PBO) fiber (ZYLON, Toyobo, Japan). The filament consists of rigid rod chain molecules of poly (p-phenylene-2, 6-benzobisoxazole), and it has a high tensile strength and a high modulus. This kind of fiber bundle has the lowest number of single fibers of the relevant fiber bundles that are available in Japan. The physical properties of the fibers are listed in *Table I*. The matrix used was 100 wt% epoxy resin (XNR6815, Nagase Chemtex Corporation, Japan), with 27 wt% hardener (XNH6815, Nagase Corporation, Japan).

TABLE I. Properties of fibers.

Fiber property (units)	UHMWPE	PBO
Density (g/cm^3)	0.97	1.56
Tensile strength (MPa)	2600	5800
Young’s modulus (GPa)	79	270
Elongation break (%)	3-5	2.5
Decitex (dtex)	1320	273

The UHMWPE fiber bundles were wrapped with PBO fiber filament using a custom winding machine. The PBO filament was wrapped on the spool rather than having a sleeve on the hollow shaft. The UHMWPE bundle passed through the center of the shaft, with the PBO filament spool rotating around it. The exerted tension of the PBO filament can be changed by adjusting the friction between the spool and the shaft, and the spacing of the filament windings can be adjusted by varying the speed of the UHMWPE bundle. The covered fiber bundle was fabricated into a unidirectional sheet using the cylinder winding method, and the areal density of the sheet was 95–105 bundles/10 cm. The composite panels were fabricated using vacuum-assisted resin-transfer molding (VARTM) to form six-layer unidirectional sheets. The composite panel specimens were designated as C-UFRP1 and C-UFRP2, made from fiber bundles prepared with and without filament-winding tension, respectively. Composites panels were also fabricated using fiber bundles with four different filament-winding-spacings, namely, 1 mm, 2 mm, 4 mm, and 6 mm. A UHMWPE fiber-reinforced composite sample was also prepared without filament wrapping, designated UFRP, for comparison.

Characterization of Composites

Compression tests were conducted on a universal test machine with a load cell (AG-20KND, Shimadzu, Japan). Specimens were compressed at a constant displacement rate of 1 mm/min according to JIS K7076 [20]. Specimens of 78-mm length were used with 35-mm-long end tabs on both ends. The gauge length of the specimen was 8 mm. The compressive specimens were 12.5-mm wide and 2.3-mm thick. A single-strain gauge was attached to the center of the specimen in the longitudinal direction to measure the compressive strain. In addition, the lateral constraint provided by the grips led to the failure observed in the gauge section for all of the specimens. All of the specimens were inspected visually for any kind of defect on the edges before selecting them for testing, and all of the compression surfaces were polished carefully using a grinding machine.

RESULTS AND DISCUSSION

Figure 3 shows a comparison of the compressive strength and modulus of the UFRP and the C-UFRP specimens. The filament wrapping process increases the compressive strength by about 15% for both the C-UFRP specimens. Furthermore, the compressive modulus C-UFRP2 specimen increased by approximately 45% compared to UFRP, while that of C-UFRP1 was almost identical to that of UFRP. The improvement in the compressive strength resulting from the use of the BPO filament is expected, as described in a previous study [19].

As shown in *Figure 4*, the compressive failure morphologies of C-UFRP1 and C-UFRP2 are different. The mechanism of the exerted tension can be explained using the model in *Figure 5*. For the case without filament-winding tension, the individual fibers within the bundle are free to buckle, as shown in *Figure 5(a)*. When the filament is wound with tension, individual fiber buckling is reduced, and the entire bundle buckles, as shown in *Figure 5(b)*; this leads to the increased modulus.

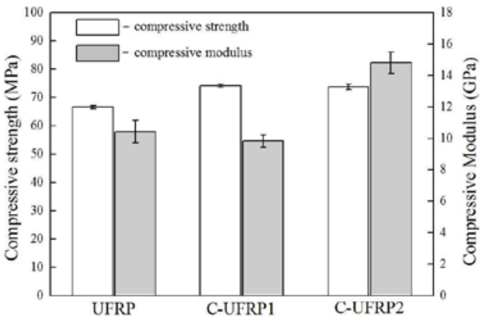

FIGURE 3. Compressive strength and modulus of specimens.

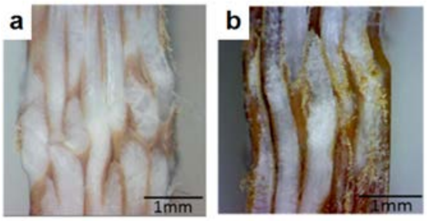

FIGURE 4. Compressive failure picture of (a) C-UFRP1; (b) C-UFRP2.

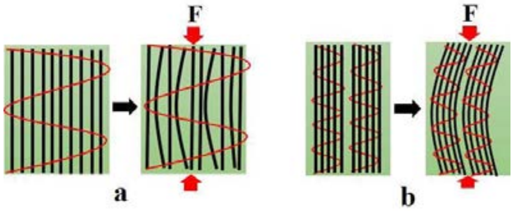

FIGURE 5. Model of fiber buckling process during compression: (a) filament wound without tension;(b) filament wound with tension.

The effect of the filament winding spacing on the compressive modulus is shown in *Figure 6*. Overall, the shorter the winding spacing, the greater is the compressive strength, and the lower is the compressive modulus. The filament restrains the bundle fibers and prevents the buckling deformation. For the same distance, more restrictions will cause more resistance, thereby enhancing the compressive properties of materials. However, the experimental results also verify that the instability of fibers in the composite is in agreement with Euler's formula.

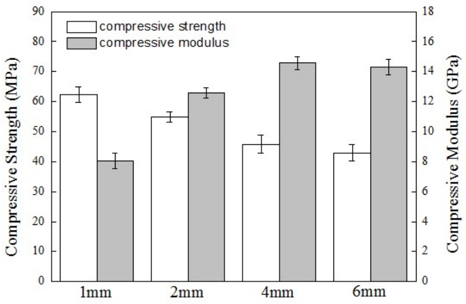

FIGURE 6. Compressive strength and modulus of specimens for different filament-winding spacings.

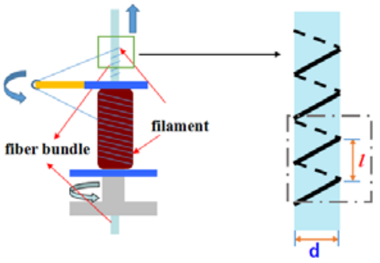

FIGURE 7. Schematic showing relation between winding angle and spacing.

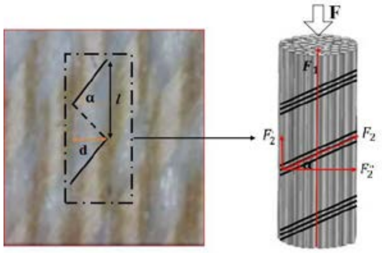

FIGURE 8. Model to illustrate the relation between winding angle and force distribution.

The difference trend in the compressive strength and modulus was attributed to the filament-winding angle during the covering process. The modulus is a parameter that is obtained at the initial stage of deformation. The models shown in *Figure 7* and *Figure 8* explain the increase in the modulus as the filament-winding spacing increases. The relation between the winding angle and winding spacing is given in Eq. (2). During the winding process, there is a certain angle between the reinforced fiber bundle and the wound filament. The angle (a) and filament-winding spacing (*l)* have a proportional relationship, as shown in the equation. The greater the filament winding spacing, the greater is the angle. The force required to resist the compressive forces F in FRP can be classified into two parts. First, F_1 is caused by reinforcing fibers, namely the UHMWPE fibers. F_2 is caused by the wound filament, namely the PBO fibers. There is a certain angle between the direction of F_2 and the horizontal direction, i.e., α. F_2 can be divided into two forces along the horizontal and vertical directions, where in the horizontal direction, it is F''_2, while in the vertical direction, it is F'_2. The relationship between them can be expressed as Eq. (3) and Eq. (4).

$$\sin\alpha = \frac{1}{\sqrt{4(d/l)^2+1}} \tag{2}$$

$$F_2^{'} = F_2 \sin\alpha = \frac{F_2}{\sqrt{4(d/l)^2+1}} \tag{3}$$

$$F_2^{''} = F_2 \cos\alpha = \frac{F_2}{\sqrt{1+l^2/4d^2}} \tag{4}$$

F'2 increases as the angle increases, or as the filament-winding spacing increases, F''_2 increases. At the same time, F'_2 depends on the mechanical properties of the PBO fiber, which has a higher modulus than the UHMWPE fiber, and additional resistance forces along the vertical direction can cause the compressive modulus of FRP to increase. In the horizontal direction, F''_2 will decrease with angle α. As the filament-winding spacing increases, F''_2 decreases, resulting in a decrease in the supporting force required to prevent the buckling of fiber bundle. To some extent, this is one reason for the decrease in the compressive strength.

The method that is used to prepare composite materials, which involves filament-wound fiber bundles, can significantly improve the compressive properties of composites without reducing the mechanical properties. Compared with 3D braided composites, filament winding has a more effective FVF, and the preparation process has less complexity, low cost, is practical, and has a wide range of potential applications.

CONCLUSION

A filament-wound fiber bundle was designed for fabrication into unidirectional fiber-reinforced epoxy resin composites, and the compressive strength and modulus of the specimens were tested. The experimental results indicate the following:

(1) The filament-winding process could increase the compressive strength by about 15%, and exerting tension during the filament-winding process could increase the compressive modulus by about 45 percent.

(2) The tension exerted during the filament-winding process could transform the fiber-buckling modes from a single-fiber buckling into a global buckling of the whole bundle.

(3) As the filament-winding spacing increases, the compressive strength of specimens will decrease due to the buckling of the longer compressive critical wavelength. Meanwhile, the compressive modulus will decrease due to lower concentration of the PBO filament.

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AUTHORS' ADDRESSES

Fangtao Ruan, PhD
Zhenzhen Xu
Dayin Hou
Li Yang
Changliu Chu
Anhui Polytechnic University
College of Textile and Fashion
Beijin Middle Road No.8
Wuhu, Abhui Province 241000
CHINA