Study on three-dimensional braided carbon fiber composite for live working on transmission lines

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Abstract. A new type of three-dimensional braided carbon fiber composite was developed by optimizing the carbon fiber composite weaving process which employs carbon fiber yarn connecting the two adjacent carbon layers of left and right 45° two-way cross. The mechanical properties and failure mechanism of the three-dimensional braided carbon fiber composite were characterized by mechanical tests and SEM. The results show that the flexural strength, compressive strength and interlaminar shear strength of the three-dimensional braided carbon fiber composite, which are as high as 750.67 MPa, 378.38 MPa and 425.6 MPa, increases by 10%, 88% and 120% compared with that of the one dimensional long fiber carbon fiber composite, respectively. The three-dimensional braided carbon fiber composite has been successfully applied to the development of the load bearing tools for live working of transmission lines, and the weights of the tools reduce more than 40% compared with the traditional tools. The successful development of this composite has laid the foundation for the preparation of light weight bearing tools for live working of transmission lines, which is of great significance to reduce the labor intensity and improve the working efficiency.

1. Introduction

Live working is an important technical measure to ensure the safe and reliable operation of transmission lines [1]. So far, live working large tonnage bearing tools are mainly made of stainless steel and titanium alloy, the weight of which is too heavy, resulting in the inconvenient operation and carrying and increases of the labor intensity. In addition, it also gives the workers buried safe risks. Especially, with the commercial operation of ultra-high voltage (UHV) transmission lines, the size and rated load of the live working bearing tools will be further increased, so it is urgent to develop new lightweight tonnage bearing tools. This paper is devoted to the development of carbon fiber composite with excellent mechanical properties, and its application to the development of live working large tonnage bearing tools.

Carbon fiber has excellent mechanical properties, its maximum tensile strength is of 7.02GPa, modulus of 296GPa, however, its density is only 1/4 of steels [2-4]. Carbon fibers are usually processed with a composite, such as or resinous material [5-7], metal [8], ceramic [9, 10], cement [11] into structural or functional materials in engineering applications. The most widely usage of the carbon fiber reinforced composite is resin-based composites [12]. The carbon fiber in the carbon fiber reinforced resin-based composite can be one-dimensional staple fiber [13], long fiber [14],...
two-dimensional carbon fiber cloth [15] and three-dimensional structure of carbon fiber block [16-18]. The carbon fiber reinforced resin-based composites prepared from one-dimensional long fiber and carbon fiber cloth has anisotropic mechanical properties and its excellent tensile property is parallel to the fiber direction. The three-dimensional braided carbon fiber composite sheet is prepared by suitably weaving the carbon fiber and then being prepared by plastic molding [17, 18], which fundamentally solved the weakness of the the traditional carbon fiber reinforced composite, such as, poor performance of the stiffness and strength along the thickness direction, low shear strength of in-plane shear and interlayer. As so far, the research of the mechanical properties of three-dimensional braided composites has become the focus of composites research [19-26]. Tan P. [19] found that the direction of the crack is perpendicular to the load direction in the destructive test, resulting in the separation of the Z yarn and the substrate in the research of the tensile properties of three-dimensional orthorhombic woven composites. Yan Y. [20] established the relationship between the fiber volume content and the value of the elasticity by observing the microstructure of the fabric, and the results show that the elastic modulus increases with the increase of the volume fraction of the veins, and the distance between the filament and the weft yarn also affects the elastic properties of the composites. Liu Q. [26] verified that the larger of the interface force between the fiber and resin contact, the better of the bending and compression performance of three-dimensional braided composite, and proposed that the structural parameters also affects the mechanical properties of the composites. In this paper, we compared the mechanical properties of two kinds of epoxy resin based composites, the reinforcement of which are one-dimensional long-fiber carbon fiber and three-dimensional braided carbon fiber sheet, respectively, and then explored their application in the live working tool.

2. Experiment

2.1 The preparation of the composites

The type of carbon fiber used in the both composites is T300. One dimensional fiber reinforced carbon fiber reinforced epoxy resin composite (one dimensional carbon fiber composite) was bought from HongYu Carbon Fiber Composites Technology Co., Ltd. The composite is made of one-dimensional long-fiber carbon fiber and epoxy resin by suitable heating and curing process.

Three-dimensional fiber reinforced carbon fiber reinforced epoxy resin composite (three-dimensional braided carbon fiber composites) was designed and developed independently using three-dimensional angle chain lock machine weaving method. The preparation process is as follows: first of all, two-dimensional carbon fiber fabric was woven by longitudinal fiber and transverse fiber. Longitudinal and transverse mixed two-way cloth adapted traditional woven carbon fiber woven fabric method with the principle of the vertical and horizontal yarn interweaved. It can be seen from Fig.1 that vertical and horizontal yarn were crossed every single yarn, separately. No.1, 3, 5, 7 of the vertical yarn is underlying while No.2, 4, 6, 8 is upward. Similarly, No.1, 3, 5, 7 of the horizontal yarn is upward while No.2, 4, 6, 8 is underlying. Then the layer of carbon fiber cloth was defined according to the requirement of the thickness of the product. Woven carbon fiber cloth was recognized as the perform product which uses carbon fiber yarn connecting the two adjacent carbon layers of left and right 45° two-way cross, as shown in Fig.2. Finally, the woven carbon fiber perform product was dipped in epoxy resin and shaped with pultrusion process to eliminate the gas to the largest extent (Fig.3).
Figure 1. The schematic diagram of the carbon fiber fabric.

Figure 2. The schematic diagram of three-dimensional carbon fiber fabric perform product. 1- Longitudinal and transverse mixed carbon fiber fabric, 2- carbon layers of left and right 45°.

Figure 3. The preparation process flow chart of three-dimensional carbon fiber woven

2.2 The tests of the samples
Both types of the carbon fiber composites were stretched, squeezed, curved, interfacially sheared and laterally sheared according to the related domestic standard of GB/T 1447-2005, GB/T 1448-2005, GB/T 1449-2005, GB/T 1450.1-2005 and GB/T 1450.2-2005. And the microstructure of the composites after destruction was observed by SEM. In order to guarantee the repetition of the test, 4-6 samples were used in every group. The sizes of the sample required in the squeezed test and density test are 30×10×10 mm, 60×20×10 mm, respectively. The sizes of the sample required in the stretched test, curve test and interfacial shear test were shown in Fig.4. Electronic universal material testing machine (DNS-300) was used to load, Data automatic collection meter (TDS-602) was used to record all the data, and resistance strain gauge was used to measure strain. The sensitivity of the electro-balance using to measure density is 0.0001g. Field emission scanning electron microscope (SIRION 200) was used to observe the micro morphology.
3. Results and Discussion

3.1 Mechanical properties tests

The tensile stress-strain curves, compressive stress-strain curves, flexural stress-strain curves and interlaminar shear stress-strain curves of the one dimensional carbon fiber composite and the three-dimensional braided carbon fiber composites are shown in Fig. 5. The results show that the compressive, bending and anti-interlaminar shear properties of the three-dimensional braided carbon fiber composites are obviously improved, especially the anti-interlaminar shear strength is improved by 220%. The transverse shear resistance remained basically unchanged, while the tensile properties decreased slightly. Generally, the tensile properties of the three-dimensional braided carbon fiber composites were significantly improved.

The maximum deformation value of the three-dimensional braided carbon fiber composite in various mechanical properties tests is basically less than that of one-dimensional carbon fiber composites, due to the increase of 45° carbon fiber filaments. The carbon fibers filaments in both directions reduce the degree of freedom of the three-dimensional braided carbon fiber composite and cut down its deformability in all directions.
Figure 5. The tensile stress-strain curves (a), compressive stress-strain curves (b), flexural stress-strain curves (c) and interlaminar shear stress-strain curves (d) of the one dimensional carbon fiber composite and the three-dimensional braided carbon fiber composites are shown in Fig. 5 (A- one dimensional carbon fiber composite; B- three-dimensional braided carbon fiber composites)

Table 1. The mechanical properties of three-dimensional braided carbon fiber composites and one dimensional carbon fiber composite

| properties                  | three-dimensional braided carbon fiber composites | one dimensional carbon fiber composite | ratio |
|-----------------------------|--------------------------------------------------|---------------------------------------|-------|
| tensile strength (MPa)      | 528.29                                           | 653                                   | 81%   |
| elastic modulus (MPa)       | $6.83 \times 10^4$                               | $9.29 \times 10^4$                    | 74%   |
| poisson ratio               | 0.51                                             | 0.33                                  | 164%  |
| compressive strength (MPa)  | 378.38                                           | 201.3                                 | 188%  |
| compressive modulus (MPa)   | $1.46 \times 10^5$                               | $7.78 \times 10^4$                    | 83%   |
| flexural strength (MPa)     | 750.67                                           | 679.4                                 | 110%  |
| elastic modulus (MPa)       | $6.34 \times 10^4$                               | $8.06 \times 10^4$                    | 187%  |
| interlaminar shear strength (MPa) | 42.56                                        | 19.38                                 | 220%  |
| Density (g/cm$^3$)          | 1.56                                             | 1.52                                  | 103%  |
3.2 Microstructure

Fig. 6 and Fig. 7 show the microstructure of the composites before and after tensile failure. As for one dimensional carbon fiber composite, carbon fiber filaments are uniformly distributed in epoxy resin substrate with an approximate parallel way. The content of carbon fiber reaches above 70%. However, larger-sized bubbles with an orientation parallel with fibers are observed in the board. Bubbles severely weaken crush resistance and interlaminar shear strength of composite. Breakpoints of carbon fiber on the fracture section are discretely distributed and not located on a plane, corresponding to the downward drop phenomenon of tensile stress in tensile stress-strain curve.

The three-dimensional braided carbon fiber composite has a fracture section perpendicular to the two-dimensional carbon fiber cloth plane. The fracture section is not smooth and breakpoints of carbon fiber bundles which are perpendicular to fracture section are located on different plane, but the discreteness of breakpoints of carbon fiber bundles is small and the breakpoints of the same bundle of carbon fiber is basically at the same plane. There are not only pull-out carbon fiber bundles, but also black holes leaved by carbon fiber bundles being pull out, as shown in Fig. 7c and Fig. 7d. Carbon fiber bundles parallel to fracture section show a ripped appearance. The longitudinal carbon fiber bundles separated from the resin but horizontal ones still maintain a good contact with the resin.

There-dimensional braided carbon fiber composite comprises four groups of fibers, including a group of longitudinal fibers, a group of latitudinal fibers and two groups of fibers parallel to the Z axis, and there is no entanglement and crimp in these four groups. Longitudinal fibers and latitudinal fibers are stretched perpendicularly in a plane, enhancing in-plane mechanical properties of the composite. Carbon fibers at 45° can greatly heighten the stability of the composite, enhance interlaminar shear strength, decrease the possibility of delamination, and furthermore, improve its bend property and fatigue performance [26, 27]. In addition, these carbon fibers are in the plane vertical to the two dimensional carbon fiber fabric, which means that the epoxy resin could wet the whole braiding along these carbon fibers and prevents the formation of holes in the composite [17]. One dimensional carbon
fiber composite has reinforcing fibers in only one direction. Consequently, only the tensile strength in the direction parallel to the fiber bundle was excellent.

4. Application

The tensile strength of three-dimensional braided carbon fiber composite is similar to that of LC4, while its density is one half of that of LC4. Based on the application of three-dimensional braided carbon fiber composite and titanium alloys, tools like hooks and closed card (Fig. 8), which is used to replace insulator string of transmission lines in live working, were designed and produced industrially. The weight of tools made in three-dimensional braided carbon fiber composite deceased at least 40% compared with traditional metal tools, which is meaningful in decreasing labor intensity and ensuring safety during live working.

With further investigations on three-dimensional braided carbon fiber composite, such as optimization of solidification technology, better adaption of carbon fiber and epoxy resin, the mechanical property of the three-dimensional braided carbon fiber composite will be improved consistently, which lays the foundation for its application in live working under ultra-high voltage.

Figure 7. The microstructure of the deformed three-dimensional braided carbon fiber composite

Figure 8. Hooks (a) and closed card (b) made from this three-dimensional braided composite
5. Conclusion
A three-dimensional braided carbon fiber composite has been developed. The comprehensive mechanical properties of this composite are obviously better than one dimensional long fiber carbon fiber, attributing to three-dimensional structure of the fiber along Z-axis. In particular, compressive strength, flexural strength, and interlaminar shear strength are improved greatly, although its tensile strength decreases slightly. Above all, the special strength of this three-dimensional braided composite by T300 is twice higher than that of LC4. At present, hooks and closed card made from this three-dimensional braided composite is applied in live working of transmission line successfully, which reduces the tool weight substantially. With further investigations of three-dimensional braided carbon fiber composite, the mechanical properties of which will be improved consistently. It could be inspected that three-dimensional braided composite has broad application prospection in transmission lines, especially in UHV live line.

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