MECHANICAL PROPERTIES TESTING OF CARBON FIBER REINFORCED COMPOSITES

Mingchun Fu[1], Xishan Yu[1], Shichao Ying[1]*
[1]Dalian Ocean University, Dalian, 116300, China.
**Corresponding author: Mingchun Fu*
Email: fumingchunucy@yeah.net

Abstract - the current research in the field of materials focuses on the analysis of the properties of carbon fiber (CF). There are relatively few studies related to the structural design of CF composite reinforcements in practical applications. In order to improve the traditional laminate structure of aircraft engine blades, CF reinforced epoxy resin matrix composites are used as the research object. Its surface modification method, toughening method, and molding process ae studied. Then, the laminate structure of aircraft engine blades is studied and designed based on CF reinforced epoxy resin matrix composites combined with the concept of bionics. The root, middle, and tip parts of the engine blade are designed with layered structure and angle. Finally, the mechanical properties of the designed blades are tested through experiments. The results show that among the three-layered design structures of the blade root, the bionic synchronous double helix structure of the blade root has the highest tensile strength, which is 419.13MPa. The bending strength of the leaf root bionic variable angle double helix structure is the highest, which is 1349.45MPa. Among the three-layered design structures in the blade, the biomimetic nonlinear structure in the leaf has the highest tensile strength and bending strength values, which are 468.23MPa and 1222.44MPa, respectively. Among the three-layered design structures of the blade tip, the tensile strength and bending strength of the blade tip bionic variable-angle double helix structure are the highest, which are 457.78MPa and 1126.33MPa, respectively. These results provide research experience for further improving the performance of aircraft engines.

Keywords: Carbon fiber, Composite material, Blade layup design, Bionics, Mechanical property testing.

1. Introduction

Composite materials play a vital role in the development of modern science and technology [1]. As a new artificial material, the performance of each component is complemented and correlated, so that the comprehensive performance of the material can meet people's needs. The International Organization for Standardization (ISO) defines a composite material as a multiphase solid material composed of two or more substances with different chemical and physical properties. Composite materials mainly include four elements: reinforcement material, collective material, molding technology and interface phase. The research on carbon fiber (CF) reinforced materials [2] began in the 1960s, and was mainly used in cutting-edge technical fields such as aerospace. CF reinforced materials are mainly used in aerospace, military, precision machinery and other fields because of their excellent properties.

Khadak, et al. (2021) [3] demonstrated how to prepare CF-reinforced composite surfaces such that the ice formed on the surface can be easily removed without using any other techniques. They fabricated unidirectional pre-impregnated CF-reinforced composites in a vacuum oven to prepare Superhydrophobic (SH) coatings containing microparticles and nanoparticles using a simple spray method. Then, the bottom (base) layer and the top (superhydrophobic) layer are introduced into the surface of the CF-reinforced composite, and heat-treated under vacuum. Pappas, et al. (2021) [4] studied the factors affecting high-speed 3D printing of continuous CF-reinforced composites, including material deposition rate, printing (Nozzle Traverse) speed and Nozzle Inclination. This method explores the effects of deposition rate, printing speed and nozzle inclination on sample quality and mechanical properties using thermoplastic pellets and continuous CF filaments as raw materials. Paul, et al. (2021) [5] studied the properties of carbon-based materials deposited under deposition and infiltration conditions by the Film Boiling Chemical Vapor Infiltration (FB-CVI) process. They developed a new type of reactor with unique properties to simulate process conditions and used a self-made reactor to deposit pyrolytic carbon on a graphite substrate. The kinetics of this process was studied in the temperature range of 1100°C - 1150°C. The properties of the carbon matrix are explored. This provides process guidance for the densification of 2D continuous fiber preforms. Hu, et al. (2021) [6] studied the effect of CF content on the mechanical properties, thermal properties and morphological properties of composites.

The results show that with the increase of CF content, the tensile properties, bending properties, hardness and thermal conductivity of CF and Polylactic Acid (PLA) composites are effectively improved compared with pure PLA. Chang, et al. (2021) [7] studied the effects of anisotropy and temperature on the mechanical properties of Short Carbon Fiber/Poly Ether - Ether Ketone (SCF/PEEK) composites. At 23°C, 80°C, 140°C and 200°C, tensile tests in different mold flow directions were carried out. The results show that temperature and fiber orientation greatly influence the tensile properties of SCF/PEEK. Both the tensile strength and elastic modulus decreased with temperature increase, and the fracture strain increased with the rise of temperature.

Most of the research results focus on CF technology and properties. Still, there are few related research results on the structural design of CF composite reinforcements in practical applications. The lay-up design of CF reinforced epoxy resin matrix composite blades is carried out bionics based on the research on CF reinforced epoxy resin matrix composites, combined with the principle of bionics. This innovative combination of the concept of bionics and the structural design of composite materials. The research results provide experience for the application of composite materials in the aerospace field.

2. Methods and Materials

2.1 CF Reinforced Epoxy Resin Matrix Composites

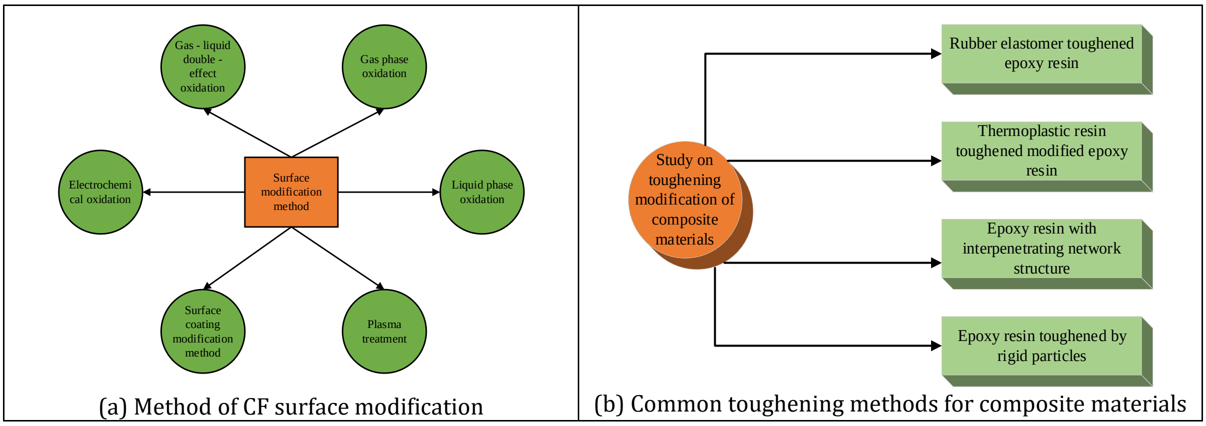
The carbon content of CF [8] is more than 95%. As a new material, it has high axial strength and modulus, high temperature resistance and chemical corrosion resistance.

In addition, it also has excellent properties such as low density, high specific performance, no creep, good fatigue resistance, low electrical resistance, high thermal conductivity, and low thermal expansion. CF is an important material used in national defense, military industry, aerospace, etc.

The molecular formula of epoxy resin [9] is $(C11H12O3)n$, which is a kind of macromolecular polymer. It is a general term for macromolecular polymers containing two or more epoxy groups in the molecule. Its epoxy group can be cured and cross-linked with a variety of compounds containing active hydrogen to form a network structure. It has the advantages of high bonding strength, wide bonding surface, low shrinkage rate, good stability, excellent electrical insulation, and good processability. It is used in coatings, electrical and electronic, composite materials, adhesives, etc. The material composed of epoxy resin as resin matrix and combined with CF reinforcement material is called CF epoxy resin composite material [10]. The research on CF reinforced epoxy resin matrix composites mainly includes: CF surface modification research [11], composite toughening modification research [12], curing and composite molding process [13] and so on.

The method of CF surface modification mainly uses physical and chemical methods. By increasing the polarity of the CF surface and making the surface morphology more complex, the interface between CF and epoxy resin is improved, and the mechanical properties of the material are improved. CF reinforced epoxy resin matrix composites are studied for toughening modification mainly because the three-dimensional network structure generated by pure epoxy resin after curing and crosslinking has large internal stress, brittleness and hardness, poor crack resistance and low toughness, poor heat and humidity resistance, low peel strength, etc. [14].

The commonly used surface modification and toughening methods of CF materials are shown in Figure 1.



(a) Method of CF surface modification

(b) Common toughening methods for composite materials

Figure 1: Common surface modification and toughening methods of CF

In Figure 1, the development of composite materials is inseparable from the molding process of composite materials. The research of composite molding process is mainly divided into two aspects. 1. Research on composite material forming technology. The main purpose is to improve the technical level as well as the stability and reliability of one-piece composite molding. 2. Design and optimize the structure of composite materials. The purpose is to reduce the construction weight and cost through further research on composite materials while meeting the requirements of use. The molding process of common composite materials is shown in Figure 2.

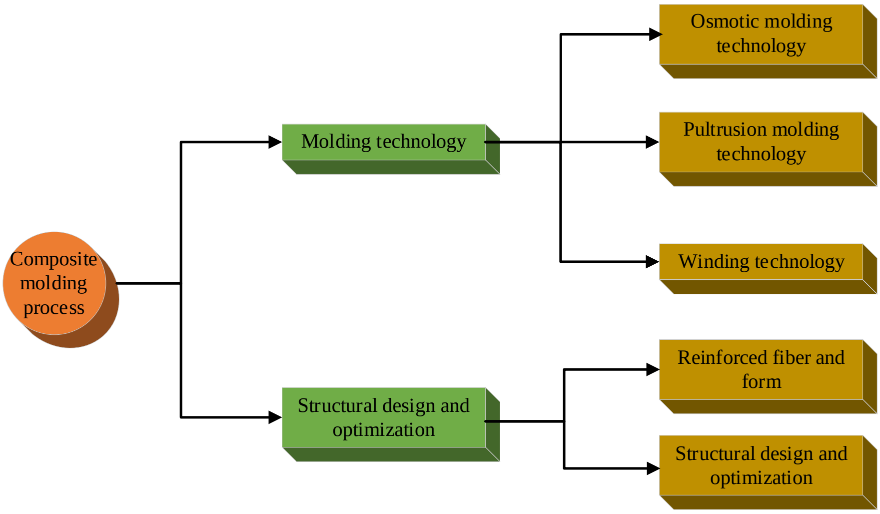


Figure 2: Forming process of composite materials

Epoxy resin-based composites are cured by crosslinking through the reaction between epoxy resin and curing agent [15]. Curing mainly includes three aspects: curing agent, curing method and curing process system.

2.2 Composite Blade

In an aircraft, the engine is an important part to maintain its normal operation and flight. The study of engine blade materials is an important branch in the field of aerospace research.

Based on the advantages of composite materials such as strong designability, high specific modulus and specific strength, and high damping, scholars have also begun to study the application of composite materials in aircraft. As early as 1965, CF composite materials have been tried to be used in the manufacture of aircraft engine blades. Up to now, research in this area has achieved many results. For example, the Yangtze River 1000 series composite blades successfully researched in China's aviation field, and the General Electric 90 (GE90) composite blades designed by the General Electric Company (GE) of the United States in the 1990s. The General Electric next-generation (GEnx) composite material designed in the early 21st century, the Loop Engine for Array Processors-X (LEAP-X) composite material blade jointly developed by the United States and France, etc.

2.3 Lay-up Design of Bionic CF-reinforced Epoxy Resin Matrix Composite Blade

Biomimicry is the invention and creation of new equipment, tools and technologies by studying and simulating the structure, function, behavior and regulatory mechanism of organisms [16]. Biomimicry research is mainly divided into three stages. Firstly, the excellent characteristics of organisms are based on the excellent characteristics of organisms that can be used for reference, and the biological structure is simplified. Then, the biological model is constructed through the simplified biological structure, and the biological model is transformed into a mathematical model through the comparison, induction and summary of the biological model. Finally, the bionic physical model is constructed through the obtained mathematical model. Based on the concept of bionics, this study uses CF reinforced epoxy resin matrix composite material as the composite material to design the thickened layer of the blade.

Firstly, the appropriate blade model is selected for the layup design of the composite blade. The GE90 blade model is selected as a reference. Metal edging has been removed from the GE90 model. The second step is to design the fill layer based on the Volume Fill module of Fibersim software. During this step, the appropriate impregnation parameters of the composite blade fibers need to be selected in advance. Weihai Guangwei T300 grade CF prepreg is selected.

The cured thickness parameter is 0.15 mm. The third step is to obtain the input direction of the fiber layup according to the bionic layup scheme. The fourth step is to divide the blade into three parts: the root, the middle and the tip for layering design. The fifth step is to judge whether the designed blade structure is reasonable. If it is unreasonable, modify the direction of fiber layup in the third step, and then repeat the actions of the fourth and fifth steps.

Finally, the obtained blade structure is guaranteed to be reasonable and meet the design requirements.

When the blade root layer is designed, three blade root structures are designed according to different biological prototypes. According to the double helix structure of coelacanth scales, the biomimetic synchronous double helix structure and the biomimetic variable angle double helix structure are designed respectively. The bionic nonlinear structure is designed according to the fiber structure of the feather shaft of the eagle owl and the nonlinear helical structure of the lobster pincer. The layup angle design of the three structures is shown in Table 1.

Table 1: Structural angle design of blade root layer of biomimetic CF reinforced epoxy resin matrix composite blade

The structure of blade root layup design	The angle of the blade root layup
The structure of the leaf root biomimetic synchronized double helix	0°, 0°, 45°, 45°, 90°, 90°, -45°, -45°, 0°, 0°, 45°, 45°
The structure of the leaf root biomimetic variable angle double helix	0°, 0°, 30°, 45°, 60°, 90°, 90°, -45°, -60°, 0°, -30°, 45°
Leaf root bionic nonlinear structure	0°, 3°, 9°, 27°, 81°, 243°, 0°, 3°, 9°, 27°, 81°, 243°

When designing the leaf middle layer of the blade, based on the blade root design, the bionic triple helix fiber layup structure, the bionic variable angle double helix fiber layup structure and the bionic nonlinear fiber layup structure are designed. The layup angle design of the three structures is shown in Table 2.

Table 2: The angle design of the layered structure in the blade of the bionic CF-reinforced epoxy resin matrix composite blade

The structure of the lay-up design in the blade	The angle of the layup in the leaf
The structure of biomimetic synchronized triple helices in leaves	0°, 0°, 22.5°, 45°, 45°, 67.5°, 90°, 90°, -67.5°, -45°, -45°, -22.5°, 0°, 0°, 22.5°, 45°, 45°, 67.5°
The structure of the biomimetic variable-angle double helix in the leaf	0°, 0°, 30°, 45°, 60°, 90°, 90°, -45°, -60°, 0°, -30°, 45°, 0°, 90°, 30°, -45°, 60°, 0°
Biomimetic nonlinear structures in leaves	0°, 3°, 9°, 27°, 81°, 243°, 0°, 3°, 9°, 27°, 81°, 243°, 0°, 3°, 9°, 27°, 81°, 243°

According to the layered structure of the blade root and the leaf, and with the blade thickening as the premise, three blade tip layered structures are designed, namely, the bionic synchronous double helix structure of the blade tip, the bionic variable angle double helix structure of the blade tip, and the bionic nonlinear structure. structure. The angle designs of the three structures are shown in Table 3.

Table 3: Angle design of blade tip layer structure of bionic CF reinforced epoxy resin matrix composite blade

The structure of blade tip layup design	The angle of the blade tip layup
Leaf tip biomimetic synchronous double helix structure	0°, 0°, 22.5°, 22.5°, 45°, 45°, 67.5°, 67.5°, 90°, 90°, -67.5°, -67.5°, -45°, -45°, -22.5°, -22.5°, 0°, 0°, 22.5°, 22.5°, 45°, 45°, 67.5°, 67.5°
Bionic variable-angle double helix at the tip of the leaf	0°, 0°, 30°, 30°, 45°, 45°, 60°, 60°, 90°, 90°, -45°, -45°, -60°, -60°, 0°, 0°, -30°, -30°, 45°, 45°, 0°, 0°, 90°, 90°
The bionic nonlinear structure of the blade tip	0°, 3°, 9°, 27°, 81°, 243°, 0°, 3°, 9°, 27°, 81°, 243°, 0°, 3°, 9°, 27°, 81°, 243°, 0°, 3°, 9°, 27°, 81°, 243°

2.4 Mechanical Properties Test of Bionic CF Reinforced Epoxy Resin Matrix Composite Blade

WDW-300 micro-control electronic universal testing machine is used as the experimental device. Laminate structures designed for root, mid-leaf, and tip designs are subjected to tensile testing. The size of the sample is shown in Table 4.

The size of the clamping end is 15 mm, the gauge length is 50 mm, and the stretching rate is 2 mm/min.

Table 4: Dimensions of the sample

Structure	Size
The structure of the leaf root layer	80mm*15mm*1.8mm
The structure of the layers in the leaf	80mm*15mm*2.7mm
The structure of the leaf tip layer	80mm*15mm*3.7mm

The tensile strength of the sample is shown in equation (1):

$$\sigma_t = \frac{p}{b \cdot h} \tag{1}$$

σ_t is the tensile strength, p is the breaking load, b is the width of the specimen, and h is the thickness of the specimen.

The tensile elastic modulus of the sample is shown in equation (2):

$$E_c = \frac{L_o \cdot \Delta p}{b \cdot h \cdot \Delta L} \tag{2}$$

E_c represents the elastic modulus in tension, L_o represents the gauge length of the sample, Δp represents the load increment of the initial straight-line segment on the load-deformation curve, and ΔL represents the deformation increment within the gauge length L_o corresponding to the load increment Δp.

The bending test is carried out on samples of the same size, and the span between the bending supports is 50mm.

The bending strength of the sample is shown in equation (3):

$$\sigma_f = \frac{3F \cdot l}{2b \cdot d^2} \tag{3}$$

σ_f is the flexural strength of the specimen, F is the failure load, l is the span of the support, b is the width of the specimen, and d is the thickness of the specimen.

The bending elastic modulus of the sample is shown in equation (4):

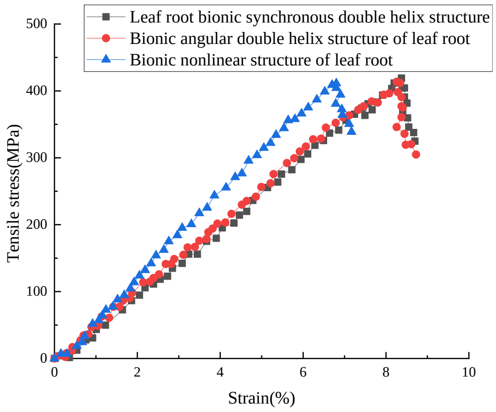
$$E_f = \frac{l^3 \cdot \Delta F}{4bd^3 \cdot \Delta S} \tag{4}$$

E_f is the flexural modulus of elasticity, ΔF is the load increment at the initial straight segment on the load-deflection curve, and ΔS indicates the deflection increment from the mid-span point corresponding to the load increment F.

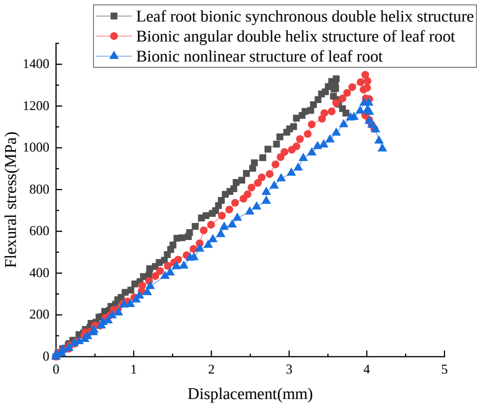
3. Experimental Results

3.1 The Test Results of the Mechanical Properties of the Blade Root of the Bionic CF-reinforced Epoxy Resin Matrix Composite Blade

The WDW-300 micro-controlled electronic universal testing machine is used to perform tensile and bending experiments on the root properties of bionic CF reinforced epoxy resin matrix composite blades, as shown in Figure 3.



(a) Tensile stress-strain curve



(b) Bending stress-strain curve

Figure 3: Mechanical properties test results of the blade root of the bionic CF-reinforced epoxy resin matrix composite blade

In Figure 3, among the three structures, the root biomimetic synchronous double helix structure has the highest tensile strength, with a value of 419.13 MPa. The strain value at the fracture is 8.37%, and the tensile strength of the bionic nonlinear structure of the blade root is the smallest, which is 411.32MPa. The strain value at break is 6.80%, while the tensile strength value of the bionic variable-angle double helix structure of the blade root lies between the two, which is 413.64 MPa. The strain value at fracture is 8.26%. Among the three structures, the flexural strength of the blade root bionic variable-angle double helix structure is the highest at 1349.45MPa, the displacement at the fracture is 3.98mm, and the flexural strength of the blade root biomimetic nonlinear structure is the smallest, which is 1214.58MPa. The displacement at the fracture is 3.97 mm, while the flexural strength of the bionic synchronous double helix structure of the blade root is 1330.24 MPa, and the displacement at the fracture is 3.61 mm.

The tensile and flexural modulus values of the three blade layup designs are shown in Figure 4.

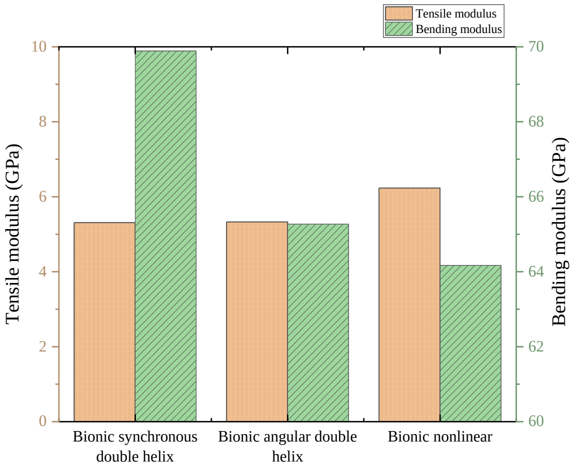
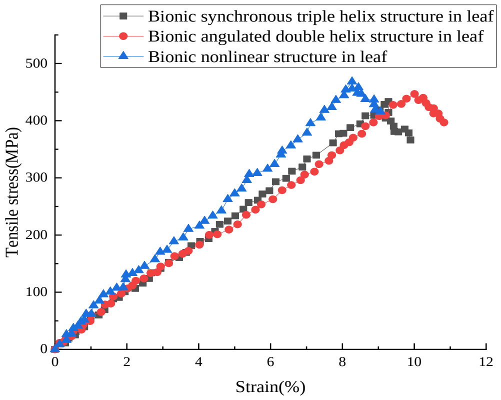


Figure 4: Tensile and flexural moduli of blade ply design structures

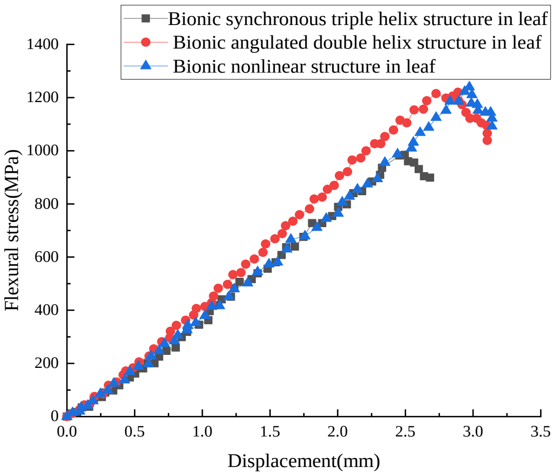
In Figure 4, among the three structures, the tensile modulus value of the blade root bionic nonlinear structure is the highest, which is 6.32 Gpa. The flexural modulus value is lower at 64.16GPa. The flexural modulus of the leaf root biomimetic synchronous double helix structure is the highest, with a value of 69.89GPa. The tensile modulus is 5.31 GPa. The tensile modulus of the leaf root bionic variable-angle double helix structure is 5.33GPa. The flexural modulus value is 65.27 GPa. Considering the tensile strength and bending strength of the three structures comprehensively, the bionic synchronous double helix structure of the blade root is given priority when designing the layered structure of the blade root.

3.2 Mechanical Properties Test Results of Bionic CF Reinforced Epoxy Resin Matrix Composite Blades

The WDW-300 micro-controlled electronic universal testing machine is used to test the tensile and bending properties of the bionic CF reinforced epoxy resin matrix composite blade leaf, as shown in Figure 5.



(a) Tensile stress-strain curve



(b) Bending stress-strain curve

Figure 5: Mechanical properties test results of biomimetic CF reinforced epoxy resin matrix composite blades

In Figure 5, the tensile strength of the bionic nonlinear structure in the leaf is the largest among the three structures, and its value is 468.23 MPa. The strain value at fracture is 8.27%. The tensile strength value of the biomimetic synchronous triple helix structure in the leaf is the smallest, which is 433.44MPa. The strain value at fracture is 9.28%. The tensile strength of the bionic variable-angle double helix structure in the leaf is 446.59MPa. The strain value at fracture is 10.01%. Among the three structures, the bending strength value of the bionic nonlinear structure in the leaf is the largest, which is 1222.44MPa.

The displacement at the fracture is 2.94mm. The bending strength value of the biomimetic synchronous triple helix structure in the leaf is the smallest, which is 984.58MPa. The displacement at the fracture is 2.50mm. The bending strength of the bionic variable-angle double helix structure is 1220.06MPa. The displacement at the fracture is 2.89 mm.

The tensile modulus and flexural modulus values of the three leaf-ply design structures are shown in Figure 6.

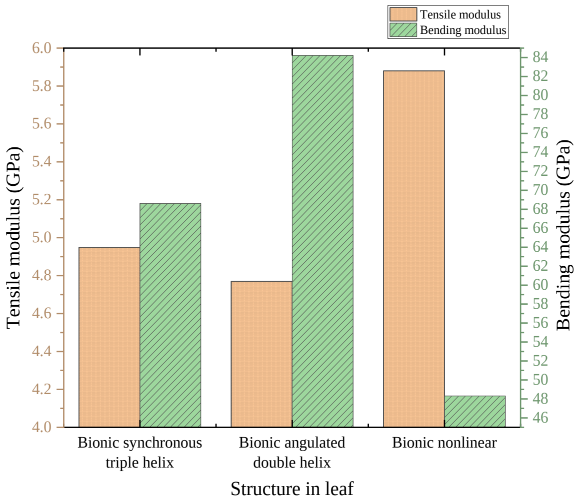
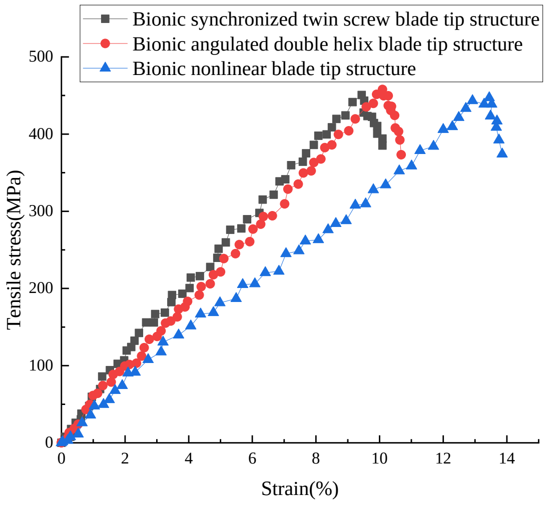


Figure 6: Tensile and flexural moduli of ply design structures in leaves

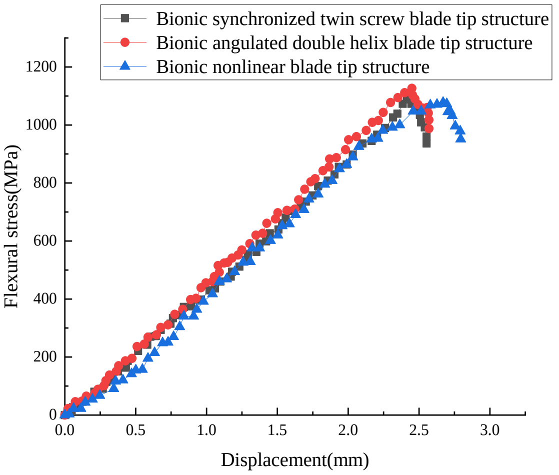
In Figure 6, the flexural modulus of the bionic nonlinear structure in the leaf is the lowest, only 48.31 GPa. The tensile modulus is 5.88 GPa. The tensile modulus and flexural modulus of the biomimetic synchronous triple helix structure in the leaf are 4.95GPa and 84.23GPa, respectively. The tensile modulus and flexural modulus of the biomimetic variable-angle double helix structure in the leaf are 5.88GPa and 48.31GPa, respectively. Considering the tensile strength and bending strength of the three structures comprehensively, the bionic variable-angle double-helix structure is given priority when laying up the middle part of the blade.

3.3 Test Results of tip Mechanical Properties of Biomimetic CF Reinforced Epoxy Resin Matrix Composite Blade

The WDW-300 micro-controlled electronic universal testing machine was used to perform tensile and bending experiments on the tip properties of bionic CF reinforced epoxy resin matrix composite blades, as shown in Figure 7.



(a) Tensile stress-strain curve



(b) Bending stress-strain curve

Figure 7: Test results of mechanical properties of bionic CF reinforced epoxy resin matrix composite blade

In Figure 7, the tensile strength value of the bionic variable-angle double helix structure of the blade tip is the largest, which is 457.78MPa. The strain at fracture is 10.09%, and its bending strength is also the highest, which is 1126.33MPa. The displacement at the fracture is 2.45mm. The tensile strength of the blade tip bionic synchronous double helix structure is slightly lower than that of the blade tip bionic variable angle double helix structure, which is 450.59MPa. The strain at fracture is 9.44%. The bending strength value is 1087.97MPa. The displacement at the fracture is 2.42mm. The tensile strength and bending strength of the blade tip bionic nonlinear structure are the smallest among the three structures, and its tensile strength is 447.11MPa. The strain at fracture is 13.45%. The bending strength is 1077.31MPa. The displacement at the fracture is 2.67mm.

The tensile and flexural modulus values of the three blade tip layup designs are shown in Figure 8.

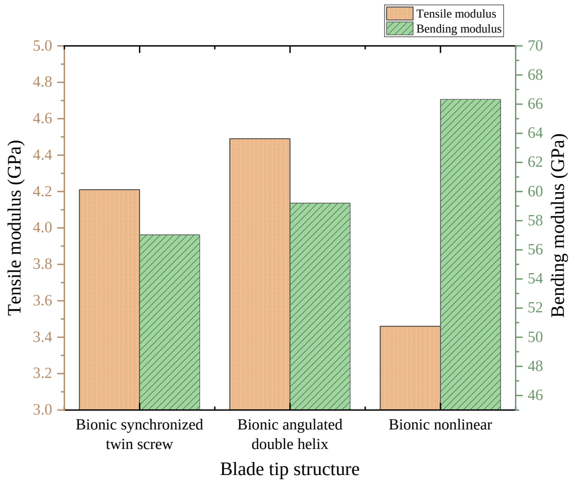


Figure 8: Tensile and flexural moduli of blade tip ply design structures

In Figure 8, the tensile modulus and flexural modulus of the bionic synchronous double helix structure of the blade tip are 4.21GPa and 57.03GPa, respectively. The tensile modulus and flexural modulus of the blade tip bionic variable-angle double helix structure are 4.49GPa and 59.21GPa, respectively. The tensile modulus is the highest among the three structures, and the tensile modulus and flexural modulus of the blade tip bionic nonlinear structure are 3.46GPa and 66.33GPa, respectively. The tensile modulus is the smallest in the seeded structure, and the flexural modulus is the largest in the three structures. Considering the tensile strength and bending strength of the three structures comprehensively, the bionic variable-angle double helix structure of the blade tip is given priority when designing the blade tip layer.

4. Conclusions

With the continuous development of science and technology, composite materials have been widely used in military industry, aerospace and other fields because of their characteristics of strong designability, light weight, and larger than mold. CF reinforced composite material is one of the most concerned composite materials. Based on CF reinforced epoxy resin matrix composites and combined with the concept of bionics, the structure of the aircraft engine blade is studied by lay-up design. Through experiments, the mechanical properties of the designed blades are tested. The results show that in the blade root part, the tensile strength of the bionic synchronous double helix structure of the blade root is the highest, which is 419.13MPa. The bending strength is 1330.24MPa.

The tensile modulus and flexural modulus are 5.31GPa and 69.89GPa, respectively. This structure is given priority when designing the blade root. In the middle part of the blade, the tensile strength and bending strength of the bionic nonlinear structure in the blade are the highest, which are 468.23MPa and 1222.44MPa, respectively. Its flexural modulus value is low, only 48.31GPa. The tensile strength and bending strength of the bionic synchronous triple helix structure are the smallest among the three structures. Therefore, the biomimetic variable-angle double helix structure is given priority when designing the layers in the blade. At the tip of the blade, the tensile strength and bending strength of the tip bionic variable-angle double helix structure are the highest, which are 457.78MPa and 1126.33MPa, respectively. The tensile modulus and flexural modulus are 4.49GPa and 59.21GPa, respectively. Therefore, this structure is given priority when designing the blade tip layup. The research results provide research experience for the material selection and design of aircraft engine blades. Some deficiencies still exist. Only the mechanical properties of the designed blade structure of the engine are studied, and the actual application of the structure to the aircraft engine is not analyzed. Further research will be carried out in the future to make the designed structure more reliable.

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