Improved strength and toughness of bioinspired Bouligand architecture composite by discontinuous carbon fiber

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Abstract. Strength and toughness are a pair of incompatible contradictions for most structure materials, and exploring the combined optimization strategy of strength and toughness of materials is a frontier research topic in the field of lightweight structure materials. Here, inspired by natural organisms, a novel hierarchical structure design scheme of the lightweight material that combines the helical layered Bouligand architecture inside the mantis shrimp rods with the "brick-mortar" staggered laminated structure of shell nacre was proposed. The deformation failure and energy absorption characteristics of this composite were compared with those of a single helical laminated structure material under bending load. It shows that, in the process of deformation and failure, the samples with both "brick-mortar" staggered laminated structure and helical laminated structure can improve their internal stress distribution and load transfer efficiency, alleviate local stress concentration and delay material failure, so as to realize the optimization of material strength and toughness. These research results have positive guiding significance for the internal structure design and performance optimization of lightweight and high-strength/toughness materials.

1. Introduction
The lightweight structural materials are of great significance for energy saving and emission reduction and reducing operating costs, and are the key materials in many high-tech fields such as aerospace, military and rail transit [1-3]. In recent years, scientists have constructed a series of new lightweight, high-strength and high-toughness composites by imitating the fine hierarchical structures of natural organisms, such as spider silk, shells and bird skulls. It provides a new way for the structural design and performance optimization of lightweight materials [4-6].

Recently, researchers have adopted the "brick-mortar" staggered laminated structure inside the mother-of-pearl layer of shellfish as a model to realize the toughening design of composite materials. In this model, the hard mineral lamellae of the "brick-mortar" laminated structure is the main bearing phase, while the flexible protein matrix mainly transmits the load by shear deformation, which ensures its effective bearing and produces a large number of deflection cracks to consume external force work at the same time, so as to achieve the optimal combination of strength and toughness [7-12]. However, it has recently been reported that there is a ferocious predator peacock mantis shrimp in the ocean, and its hammer-shaped claw can easily break the hard shells of shellfish [13,14]. The study shows that there is a kind of helical laminated Bouligand architecture inside the mantis shrimp rod, and its interlayer helical arrangement structure can effectively prevent the longitudinal propagation of cracks under external load, thus improving its overall bearing capacity and energy absorption characteristics.
It shows that the "brick-mortar" staggered laminated structure of shell nacre and the helical laminated structure of the mantis shrimp rods have their own advantages in preventing the propagation of intralayer and interlayer cracks, respectively. Therefore, it is expected to obtain lightweight structural materials with better intralayer and interlayer mechanical properties through the combined design of these two structures. At present, researchers have carried out related studies on the "brick-mortar" staggered laminated structure of shell nacre and the helical laminated structure inside the mantis shrimp rods. For example, researchers used optimized micro-nano components such as graphene oxide, alumina nanosheets, carbonate laminates and PVA, or used 3D printing technology to prepare "brick-mortar" staggered laminated shell materials [17-19], and used carbon fiber reinforced composites, polyethylene fiber composites to prepare helical laminated structure [20-23], and the load-bearing and energy absorption characteristics of the two structures were studied. However, there are still few reports on the combined design and performance of the helical laminated structure that combines the mantis shrimp rod and the "brick-mortar" laminated structure of shell nacre.

In this paper, the carbon fiber epoxy resin was used as raw material. The new composite of biomimetic layered Bouligand architecture composite with "intra layer discontinuity-interlayer helix" was prepared by laminated curing method by imitating the internal hierarchical structure characteristics of mantis shrimp and mother-of-pearl. It shows that compared with the simple "intralayer continuous-interlayer helix" biomimetic mantis shrimp helical structure material, the "intralayer discontinuity-interlayer helix" composite structure, which has the characteristics of the internal hierarchical structure of mantis shrimp and mother-of-pearl shell, can optimize the stress distribution within the layer, alleviate the local stress concentration, and enlarge the crack deflection and failure area, so as to maximize the bearing capacity of the whole structure, and realize the further optimized combination of its strength and toughness.

2. Materials preparation and characterization

In this paper, the material used for sample preparation is unidirectional carbon fiber prepreg (carbon fiber: T700, the mass ratio of carbon fiber to epoxy is 40:60), which is a carbon fiber reinforced composite layer made of carbon fiber bundle and epoxy resin. The samples of helix structure of continuous fiber (HSCF) and helix structure of discontinuous fiber (HSDF) were designed and prepared. Among them, the samples of HSCF are laminated by 16 layers of carbon fiber prepreg thin layer (size: 105mm × 105mm, thickness: 0.02mm) according to the interlayer helix angle of 12°, 24°, 45° and 90°, respectively. The only difference between the samples of HSDF and the samples of HSCF is that in the laminated sample with different helix angles, the carbon fiber prepreg of each single layer will be cut into discontinuous strips with the same length of 7 segments (105mm × 15mm, the length along the carbon fiber direction is 15mm), as shown in figure 1 (A). Finally, these samples were solidified in the oven after mold pressing and vacuum defoaming. During the curing process, the temperature was raised from room temperature to 120 °C at a heating rate of 0.5 - 1 °C/min, and kept at 120 °C for 90 minutes, then naturally cooled to 60 °C for demoulding. The manufacturing process of all samples is the same.

The mechanical test of static bending of the prepared samples were tested on the Instron3344 material mechanical properties testing machine (see figure 1 (B)). During the experiment, the samples were clamped between two steel plates to provide a peripheral fixing constraint (here is a circular hole with a diameter of 60 mm in the center of the plates). The loading rate is 1mm/min, and the test terminates when the applied load decreases by more than 40% of the max value, and the experimental result of each sample is the average of the test results of the three specimens.
3. Results and discussion

The test results of the mechanical properties of each sample are shown in figure 2. Figure 2 (A)-(C) shows the "load-displacement" curve, the max load and energy absorption results of each sample, respectively. First of all, it can be found from figure 2 (A) that the load-displacement curves of all samples show a zigzag upward trend, indicating that both HSDF and HSCF samples have progressive failure characteristics (which helps to improve their energy absorption properties), but the failure of HSCF samples occurred earlier than that of HSDF samples. Secondly, from the perspective of bearing capacity, when the interlayer helix angle is 90°, the max load value of HSDF sample is less than that of HSCF sample. With the decrease of the interlayer helix angle, the max load value of the two kinds of structure samples increases. When the interlayer helix angle decreases to 12°, the bearing capacity of HSDF and HSCF samples reaches the peak values of 1905.65N and 1606.82N, respectively, but the bearing capacity of HSDF samples is higher than that of HSCF samples. In addition, in terms of energy absorption characteristics, when the interlayer helix angle is 90°, the absorption energy value of HSDF sample is less than that of HSCF sample. With the decrease of the interlayer helix angle, the energy absorption of the samples increases, but the growth trend of the HSDF samples is faster than that of the HSCF samples. When the interlayer helix angle decreases to 12°, the energy absorption of the HSDF sample (2074.98 mJ) is significantly higher than that of the HSCF sample (1629.18 mJ).

The above results show that with the decrease of interlayer helix angle, the bearing capacity and absorption energy of HSDF samples are larger than that of HSCF samples. In order to further analyse the difference between them, the failure morphologies of these two kinds of samples were also observed, as shown in figure 3. It can be found that with the decrease of the interlayer helix angle, the cracks of the two kinds of structural samples gradually change from a relatively smooth straight line to a zigzag shape, which will promote energy absorption in the process of damage and failure, so as to...
improve toughening effect. However, the crack of HSDF samples has more zigzag deflection at the place of failure, which will cause more fracture surface and prolong the propagation path of crack, so that the fracture work absorbed by the material during failure can be further improved and the toughening effect of the material will be more obvious.

![Figure 3. Failure morphology of HSCF and HSDF samples with different interlayer helix angles.](image)

Because the material system and the helix angle of each sample in this paper are exactly the same, the only difference is whether the fibers in the layer are continuous or not. This shows that the continuity of the fibers in the layer has an important influence on the mechanical properties such as load-bearing and energy absorption properties of the materials. The possible mechanical influence mechanism of this factor will be further analyzed below.

| Property                      | Value | Units |
|-------------------------------|-------|-------|
| Modulus, $E_1$               | 107   | GPa   |
| $E_2=E_3$                    | 7.99  | GPa   |
| Shear modulus, $G_{12}=G_{13}$| 4.00  | GPa   |
| $G_{23}$                      | 3.50  | GPa   |
| Poisson's ratio, $v_{12}=v_{13}$| 0.32  |       |
| $v_{23}$                      | 0.45  |       |

According to the principle of mechanics, different structures have an important influence on the internal load transfer, stress distribution and other mechanical parameters of the material, and may lead to significant differences in the final bearing capacity, failure form and energy absorption of the material. In order to obtain the detailed full-field mechanical parameter distribution information of these two kinds of structural materials, and then study the deformation and failure mechanism of these two structures, the finite element numerical simulation method (software: ABAQUS/Standard) is used to carry out the research. All models adopt four-sided fixed constraints, which are the same as these samples in mechanical loading experiments. The material parameters of the model are shown in table 1. Each monolayer is orthotropic homogeneous material (the direction of carbon fiber is set as the main direction of the material), and its size is consistent with the experiment. Each model has 8 layers, and the meshing type of the model is C3D8R. For comparison between samples, all samples exert the same external load, and the simulation results are shown in figure 4.
From figure 4, it can be found that from the perspective of the tensile stress $S_{11}$ in the layer, the stress distribution area of $S_{11}$ in the simulation results of the HSDF samples is larger, which will improve the load transfer efficiency in the layer and make the load distribution wider, so that more materials in the layer will participate in the process of bearing and resisting deformation and failure. In the simulation results of HSCF samples, the stress of $S_{11}$ is more concentrated, and the peak value of $S_{11}$ is larger. While in the simulation results of HSDF samples, the stress of $S_{11}$ is dispersed, and the stress of $S_{11}$ is discontinuous. Although the max value of $S_{11}$ in Ply3, 5 and 7 is larger than that of the corresponding layer of HSCF samples, the stress distribution area of $S_{11}$ is larger in the simulation results of HSDF samples. It shows that under the same load, the $S_{11}$ stress of the HSDF samples is distributed to more elements in each single layer, which will alleviate the local stress concentration and delay the failure of the material, thus increasing the overall bearing capacity of the material.

From the point of view of interlaminar shear stress, it is found that the interlaminar shear stress concentration in HSCF samples is very significant, and the concentrated area is mainly distributed near the loading point. While in HSDF samples, the interlaminar shear stress concentration is limited, and the shear stress is distributed to the discontinuous joints in each layer. In the simulation results of HSCF samples, most of the interlaminar shear stress are larger, so HSCF is more likely to cause interlaminar shear failure due to the influence of interlaminar shear stress. However, under the same external load, the interlaminar shear stress $S_{13}$ of HSDF is relatively small and discontinuous, indicating that the interlaminar shear stress of HSDF is less affected by interlaminar shear stress, so it can bear larger load and absorb more external work to achieve the effect of toughening.

### 4. Conclusion

In this paper, a new type of structural composite materials with both the Bouligand architecture structure arranged spirally in the mantis shrimp rod and the "brick-mud" laminated structure in the pearl layer of the shell were prepared, and its deformation failure and energy absorption characteristics under bending load were studied. The results show that the layered composites with both "brick-
mortar" staggered laminated structure and spiral laminated structure have improved in terms of load-bearing capacity and energy absorption, which is closely related to the discontinuous fiber structure in the layer. The discontinuous distribution of tensile stress in the layer can effectively alleviate the local stress concentration in the layer and delay the failure of the material. At the same time, this "interlayer discontinuity-interlayer helix" structure distributes the interlayer shear stress to the discontinuous connection part of each layer, which alleviates the concentration of interlayer shear stress. These mechanisms may have an important impact on the load-bearing and energy absorption of the structure. The combination of two kinds of biological structures in this work is of positive significance to the design and performance optimization of lightweight structural materials, and is expected to be applied in aerospace, new energy and other fields.

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