PAPER

Design optimization of lightweight structures inspired by the rostrum in Cyrtotrachelus buqueti Guer (Coleoptera: Curculionidae)

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Abstract

The rostrum of Cyrtotrachelus buqueti Guer has excellent mechanical properties, such as high-specific strength and high-specific stiffness, and it is an example of successful evolution in nature. In this paper, based on the biological structural characteristics of the rostrum, bionic variable-density lightweight structures of varying layer number are designed, and their mechanical properties are analyzed under different helix angles. The results show that when the helix angle is greater than or equal to 40°, the maximum compressive load borne by the three-layer tube is 30.75 N, which is 1.89 times that of the single-layer tube. Through calculation, at a helix angle of 15°, the torsion lightweight coefficient of the single-layer, double-layer, and three-layer structures is 0.99 ± 0.03 N·M·g⁻¹, 1.75 ± 0.05 N·M·g⁻¹, and 2.32 ± 0.06 N·M·g⁻¹, respectively, where that of the three-layer structure was approximately 2.34 times that of the single-layer structure. Further calculations show that the bending lightweight factor of the single-layer, double-layer, and three-layer tubes is 17.89 ± 0.20 N·g⁻¹, 33.16 ± 0.45 N·g⁻¹, 41.33 ± 0.55 N·g⁻¹, respectively, where that of the three-layer tube is 2.31 times that of the single-layer tube. In addition, this paper also investigates the cushioning energy absorption characteristics of the bionic lightweight tubes by using an impact testing machine. The results show that under the same conditions, as the number of layers of the lightweight tube increases, the buffering energy absorption also increases. The total energy absorption and specific energy absorption of the three-layer lightweight tube are approximately 10 times those of the single-layer tube. Finally, a response surface-based optimization method is proposed to optimize the bionic structures under a combined compression-torsion load. The results lay the foundation for the lightweight design of thin-walled tube structures.

1. Introduction

Lightweight high-performance structures (e.g., high specific strength, specific stiffness, and damage resistance) have good prospects in high-tech industries such as in aerospace, space exploration, military, and biomedical applications (Zhang et al 2019, Liang et al 2022, Wang et al 2022). Reducing weight can lower energy consumption and manufacturing costs, which has become critical for realizing various design schemes. To ensure the good performance of structures and materials, reducing the mass and improving the payload are common goals in many fields (Plocher & Panesar, 2019, Wang et al 2019). However, traditional homogeneous material structures and their corresponding design methods have been unable to meet the requirements of complex extreme load conditions and particular circumstances.

Nature, via continuous evolution and natural selection, has evolved to take advantage of minimal resources to achieve maximal function and serves as an endless source of inspiration for humans in developing technology (Martin et al 2015). Almost all natural creatures have unique skills and gifts that help them adapt to difficult
conditions, exhibiting harmonization and unification between structure and function owing to various multi-functional macro/micro lightweight structures, composite biomaterials, and appropriate motions (Tabunoki et al. 2016). Therefore, by learning from nature, these lightweight structures with excellent mechanical properties become sources of inspiration in fabrication. For example, the outstanding mechanical performance of beetle elytra (i.e., lightweight performance, energy absorption, high intensity, toughness, anisotropy, and the ability to self-heal) (Du et al. 2020, Rivera et al. 2020) may provide useful insight into the design and manufacturing of composite materials for use in lightweight micro aerial vehicles or energy-absorbing applications (Salami et al. 2016, Isakhani et al. 2020, Rivera et al. 2021). To engineer new lightweight structures, an inspired model based on the structure of feather barbs was designed, and its effectiveness was verified both experimentally and theoretically (Sullivan et al. 2016). Hu et al. 2019 created a new type of lightweight soft robotic gripper inspired by the leaf structure and head-formation mechanisms of cabbage. These works realized the unified design of the structure, function, driving, and fabrication of robotics, and have also yielded plant-like or plant-inspired robotic solutions.

With the rise of bionic design means, many scholars have been inspired by the structural characteristics of animals and plants in nature and designed a series of excellent lightweight structures. Currently, lightweight and high-strength tubular structures are widely used in various engineering fields, such as automobiles, aerospace, and military equipment, and they are a hotspot of current research. For example, Yin et al. 2015 from Hunan University and others designed a bionic thin-walled tube based on the cross-sectional morphology of different plants and studied its impact resistance. At the same time, the tube was also optimized using a multi-objective particle swarm optimization algorithm and compared with traditional circular and square structures. The results showed that the bionic structure outperformed the traditional structures in terms of energy absorption. Also inspired by nature, Sven et al. 2015 designed a variety of bionic tubular structures based on bionic principles and applied them to robotic arms. Du et al. 2020 designed and modeled a variety of bionic thin-walled honeycomb structures with curved hollow tubes and investigated their energy absorption performance. The results showed that at wall thicknesses of 0.6 mm and 1.4 mm, the energy absorption values of the bionic structure were approximately 1500 J and 6100 J, respectively, which could be applied in automotive passive safety. Ma et al. 2021 proposed a series of corrugated tubes inspired by the micro-structure of horse-hoof wall. The results indicated that the bionic structures had improved crushing behavior and mechanical performance. In addition, many scholars have also studied thin-walled structures with different cross-sections (e.g., square, circular, triangular, quadrilateral, hexagonal, octagonal, convex polygon, concave polygon, multi-cell, and elliptical) (Hu et al. 2019, Gong et al. 2020) inspired by plants (Bührig-Polaczek et al. 2016, Chen et al. 2018, Zou et al. 2018, Fu et al. 2019, Ha et al. 2019, Song et al. 2020), animals (Wang et al. 2018, Zhang et al. 2018, Ha et al. 2019, Liu et al. 2022), or a combination of these (Albak et al. 2021, Zhang et al. 2021), and concluded that the bionic structures had good mechanical properties and impact resistance.

Cyrtotrachelus buqueti Guer is classified in the phylum Arthropoda, class Insecta, order Coleoptera, and family Curculionidae, and its weevil rostrum is a successful product of evolution (Li et al. 2019). Our previous works have shown the rostrum is a hollow multi-layer cylindrical structure, which is composed of an exocuticle layer (EXO) and an endocuticle layer (END). It was found that END consists of many layers and exhibits a typical ‘balken’ type microstructure. This structure has excellent mechanical properties, high specific strength, and high specific stiffness.

Therefore, bearing the above observations in mind, in this study, a series of bionic variable-density lightweight structural tubes inspired by the morphological and structural characteristics of the rostrum in C. buqueti Guer (Coleoptera: Curculionidae) was proposed, and its mechanical properties were investigated using finite element analyses (FEAs) and testing under compression, torsion, and bending loads. Additionally, the impact characteristics of the bionic lightweight tubes were investigated. Finally, the proposed bio-inspired structure was optimized using response surface methodology (RSM). The results obtained have high significance for the design of lightweight structures and potential for thin-walled structures in robot arms for aerospace engineering and other tubular structures.

### Table 1. Thickness of each layer of the rostrum (μm) (Xu et al. 2017).

| Layer | Thickness ± | Layer | Thickness ± | Layer | Thickness ± |
|-------|-------------|-------|-------------|-------|-------------|
| A     | 26.80 ± 0.53 | B3    | 16.08 ± 0.99 | B7    | 5.48 ± 0.32 |
| C     | 6.01 ± 0.70  | B4    | 12.95 ± 1.01 | B8    | 4.79 ± 0.53 |
| B1    | 26.80 ± 0.37 | B5    | 9.42 ± 0.52  | B9    | 3.20 ± 0.16 |
| B2    | 21.30 ± 1.31 | B6    | 7.21 ± 0.44  | B10   | 2.59 ± 0.18 |
2. Materials and methods

2.1. Bio-inspired design

Our previous works indicated the dimensions of the EXO and END of the rostrum (Xu et al. 2017). The results showed that the EXO diameter is $510 \pm 18.24 \mu m$, and the END diameter is $315 \pm 11.73 \mu m$. The average thickness of each layer in the cross section is shown in table 1.

In table 1, $A$ represents the thickness of the EXO, and $B$ and $C$ represent the thickness of the END, where $B_i$ represents the thickness of the $i$th layer from the outside to the inside in the radial direction, and $C$ represents that of the circumferential direction, which is basically constant.

Considering the many layers of the rostrum of the weevil and the feasibility of manufacturing technology, the design of bionic lightweight tubes in this paper is limited to a three-layer structure. At the same time, to study the influence of helix angle on structural mechanical properties, we set the helix angle of a single-layer tube as $10^\circ, 15^\circ, 20^\circ, 25^\circ, 30^\circ, 35^\circ, 40^\circ, 45^\circ, 50^\circ, 55^\circ,$ and $60^\circ$. The helix angle of a double-layer tube is set as $\pm 10^\circ, \pm 15^\circ, \pm 20^\circ, \pm 25^\circ, \pm 30^\circ, \pm 35^\circ, \pm 40^\circ, \pm 45^\circ, \pm 50^\circ, \pm 55^\circ,$ and $\pm 60^\circ$. The three-layer tube structure is also an alternate arrangement of these angles. For example, the three layers of a three-layer tube structure can be $+10^\circ, -10^\circ, +10^\circ$; or $+15^\circ, -15^\circ, +15^\circ$. The designed bionic structures are shown in figure 1. All tube structures have the same wall thickness, length, internal and external diameter, and porosity (all 40%), and the model decreases in turn according to the variable density ratio $q = 0.77$.

2.2. Lightweight numbers

In this paper, the porosity of all the designed bionic structures is the same, 40%, which can be calculated from the following formula:

$$
P_{\text{porosity}} = \frac{V_{\text{apparent}} - V_{\text{real}}}{V_{\text{apparent}}},
$$

where $P_{\text{porosity}}$ represents porosity, $V_{\text{apparent}}$ represents the apparent volume, and $V_{\text{real}}$ represents the real volume.

Due to the equivalent apparent volume and cross-sectional area of each bio-inspired structure, the evaluation efficiency also can be determined by lightweight numbers (LWN) as follows:

![Figure 1. Bionic variable-density lightweight tube. (a) Single-layer tube with a porosity of 40%; (b) Double-layer tube with a porosity of 40% and $q = 0.77$; (c) Three-layer tube with a porosity of 40% and $q = 0.77$.](image-url)
2.3. Structural crashworthiness criteria

The crashworthiness design of a thin-walled structure must meet the following requirements: ① good energy absorption capacity, and ② the load transmitted to the protected structure during impact is lower than the allowable load. To evaluate the crashworthiness of a bionic structure, it is essential to define the crashworthiness criteria, which typically comprise total energy absorption ($E_{\text{total}}$), specific energy absorption ($S_{\text{EA}}$), mean crushing force (MCF), and maximum crushing force (MCF).

Total energy absorption ($E_{\text{total}}$) represents the total energy absorbed by the structure during impact deformation, reflecting the energy absorption capacity of the structure. The calculation formula is as follows:

$$E_{\text{total}} = \int_{\Omega} E(\varepsilon) d\Omega,$$

where $E(\varepsilon)$ represents the strain energy density of the structure, and $\Omega$ represents the volume of the structure.

Specific energy absorption ($S_{\text{EA}}$) is often used to estimate the energy absorption capabilities of structures. $S_{\text{EA}}$ denotes the energy absorbed per unit mass of the absorber, which can be calculated as:

$$S_{\text{EA}} = \frac{E_{\text{total}}}{M},$$

where $M$ is the total mass of the structure, and $E_{\text{total}}$ is the total energy absorbed by the structure.

Mean crushing force (MCF) represents the average load level of the structure throughout the entire energy absorption process. The calculation is as follows:

$$MCF = \frac{E(d)}{d},$$

where $E(d)$ represents the energy absorbed at a certain impact distance, and $d$ is the impact distance.
3. Results and discussion

3.1. Investigation of mechanical properties of bio-inspired structures

In this paper, ANSYS Workbench 18.2 is used to analyze the compression, torsion, and bending properties of the bionic structures. The static structural module is used in the simulation module, and the material properties are given according to the photosensitive resin material for the 3D printing of the actually prepared sample, which are provided by the manufacturer, as shown in table 2. To determine the yield strength and stress-strain curve of the resin material, tensile tests were carried out, as shown in figure 2.

A Form 2 desktop 3D printer (Formlabs, China, Shenzhen) was used to prepare the samples. The printer was based on the working principle of stereo lithography, and its appearance and a flowchart of its fabrication methods are presented in figure 3.

The printing size was 145 mm × 145 mm × 175 mm, and the laser spot diameter was 140 μm. The printing was fine and stable, and the minimum layer thickness was 25 μm. The thickness of the middle layer was...
0.05 mm. Single-layer, double-layer, and three-layer bionic structure samples were printed with the photosensitive resin material (Formlabs Grey Resin V4), and the size of the sample was the same as that of the simulation model (figure 4). Finally, the mechanical properties were tested by a universal testing machine, and the test results were compared with the simulation results.

Figure 5. Single-layer compressive load displacement diagram.

Figure 6. The maximum compressive load of different-layered variable-density structural tubes at different helix angles. (a) Single-layer tube; (b) Double-layer tube; (c) Three-layer tube; (d) Comparison of the compressive capacity of three bionic tubes.
3.2. Compression performance

To study the compression performance of the bio-inspired structures, three bionic structures with different helix angles of 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°, 50°, 55°, and 60° are analyzed in this paper. The bottom surface of the model was fixed by quasi-static compression. A displacement load was applied downward along the central axis at the upper end, and grid convergence tests were carried out at the same time. Finally, the reaction force of the fixed-end surface of the structure was obtained. Taking a single layer of the 15° structure as an example, the compression finite element model is shown in figure 5. Because the quality of the simulation models in this paper is the same, according to the definition of lightweight coefficient, there is only a relationship between the maximum load and lightweight coefficient, so the simulation results only give the maximum load value. A load velocity of 2 mm min⁻¹ was set to carry out the compression tests, and force-displacement curves were obtained. The final results are shown in figure 6.
Figure 6 shows the maximum compressive load that the three kinds of variable-density light bionic structures can bear under different helix angles. It can be seen from figures 6(a)–(d) that the maximum compressive load borne by the structure decreases with the increase of spiral angle under the same internal and external diameters, wall thickness, and porosity. When the helix angle is 10°, the compressive capacity of the three structural tubes reaches a maximum of 39.26 N, which is 1.10 times that of the double-layer tube and 1.16 times that of the single-layer tube. When the helix angle is greater than or equal to 40°, the maximum compressive load borne by the three structures remains basically unchanged. At this time, the maximum compressive load borne by the three-layer tube is 30.75 N, which is 1.89 times that of the single-layer tube, 1.40 times that of the double-layer tube. It can be seen that delamination is conducive to improving the compressive capacity of the structure.

To verify the reliability of the simulation analysis, compression tests of the structural samples were carried out at the same time. A CMT5105 electronic universal testing machine (figure 7(d)) was used for the tests, with a maximum test force of 300 kN. Because the material properties, grid size, and boundary-condition settings of each simulation model were identical, this paper only tests the mechanical properties of the single-layer 15°, double-layer 15°, and three-layer 15° bionic structures.

The results from the experimental and simulated compression tests are given in table 3, which showed that, when the helix angle was 15°, the maximum compressive load borne by the single-layer, double-layer, and three-layer bionic structures was 28.4 ± 1.56, 35.18 ± 0.51 kN, and 39.56 ± 0.34 kN, respectively, and the relative error associated with the finite element calculation results was less than 6%. The simulation results are in good agreement with the experimental results, which shows that the finite element model is reliable. In addition, according to the experimental results, at a helix angle of 15°, the compression lightweight coefficient (LWN-C) of the single-layer tube, double-layer tube, and three-layer tube was 262.26 ± 15.07 N g⁻¹, 322.45 ± 4.15 N g⁻¹, and 360.76 ± 3.18 N g⁻¹, respectively. The LWN-C of the three-layer bionic structure was the largest at approximately 1.38 times that of the single-layer bionic structure and 1.12 times that of the double-layer bionic structure, and that of the double-layer bionic structure was approximately 1.23 times that of the single-layer bionic structure.
3.3. Torsion performance

The torsional performance of the single-layer, double-layer, and three-layer light bionic structures under different helix angles is simulated and analyzed. The constraint conditions and loading methods simulate the static torsion experiment. The six degrees of freedom at one end of the model are fully constrained, and angular displacement is applied on the other end of the model. Given the torsion angle, the torsional load can be obtained by fixing the reaction torque of the end face. Therefore, the torsional loads borne by the different light bionic structures under different helix angles are determined, as shown in figure 8.

Overall, the torsion resistance of the single-layer, double-layer, and three-layer bionic structures first increases and then decreases with the increase of the spiral angle, but the torsional load of the single-layer tube is the largest when the spiral angle is 40°, whereas that of the double-layer tube and three-layer tube occurs at 35°.

![Figure 8: Comparison of experimental results with simulation results.](image)

**Figure 9.** Comparison of experimental results with simulation results: (a) Single-layer tube; (b) Double-layer tube; (c) Three-layer tube; (d) Torsional experimental setup.

| Type       | Samples   | Mass (g) | Maximum torsional load (N·m) | LWN-T (N·mg⁻¹) |
|------------|-----------|----------|------------------------------|----------------|
| Single-layer | Sample #1  | 107.62   | 110.58                       | 1.03           |
|            | Sample #2  | 108.25   | 104.65                       | 0.97           |
|            | Sample #3  | 109.11   | 106.78                       | 0.98           |
|            | Simulation values | 107.26 | 100.20                       | 0.93           |
| Double-layer | Sample #1  | 109.63   | 186.34                       | 1.70           |
|            | Sample #2  | 108.67   | 191.05                       | 1.76           |
|            | Sample #3  | 109.32   | 195.89                       | 1.79           |
|            | Simulation values | 107.37 | 180.20                       | 1.68           |
| Three-layer | Sample #1  | 109.22   | 245.26                       | 2.25           |
|            | Sample #2  | 109.53   | 255.54                       | 2.33           |
|            | Sample #3  | 108.98   | 258.27                       | 2.37           |
|            | Simulation values | 108.64 | 253.30                       | 2.33           |
However, for these three structures, the torsion resistance of the single-layer tube is greatly affected by the helix angle, whereas this influence on the three-layer structure is less. The three-layer tube can bear the largest torsional load, followed by the double-layer tube. Similarly, the torsion resistance of the $15^\circ$ spiral angle lightweight tube structures were tested. A CTT500 microcomputer-controlled electronic torsion test machine was used, and its maximum test torque was 500 N·M. The test results and experimental device are shown in figure 9.

It can be seen from table 4 that the maximum torsional loads borne by the single-layer, double-layer, and three-layer tubes were 107.34 $\pm$ 3.00 N·m, 191.09 $\pm$ 4.78 N·m and 253.02 $\pm$ 6.86 N·m, respectively, and the error was less than 10% compared with the simulation. The results of the experiments and simulations were basically consistent, which showed that with more layers, the maximum torsional load that the structure could bear increased. The maximum torsional load of the three-layer structure was approximately 2.36 times that of the single-layer structure and 1.32 times that of the double-layer structure, and that of the double-layer structure was approximately 1.78 times that of the single-layer structure. Through calculation, at a helix angle of $15^\circ$, the torsion lightweight coefficient (LWN-T) of the single-layer, double-layer, and three-layer structures was 0.99 $\pm$ 0.03 N·M·g$^{-1}$, 1.75 $\pm$ 0.05 N·M·g$^{-1}$, and 2.32 $\pm$ 0.06 N·M·g$^{-1}$, respectively. The LWN-T of the three-layer structure was approximately 2.34 times that of the single-layer structure and 1.33 times that of double-layer structure, and that of the double-layer structure was approximately 1.76 times that of the single-layer structure. Thus, the multi-layer variable-density structure had better torsional performance.

### 3.4 Bending performance

Similarly, in this paper, the bending resistance of bionic lightweight tubes with helix angles of $10^\circ$, $15^\circ$, $20^\circ$, $25^\circ$, $30^\circ$, $35^\circ$, $40^\circ$, $45^\circ$, $50^\circ$, $55^\circ$, and $60^\circ$ are investigated. The porosities the of the single-layer tube, double-layer
tube, and three-layer tube are all 40%, and their material properties are the same as above. The finite element model of three-point bending is shown in figure 10, where the shell 181 cell type is chosen, and the contact-part of the mesh is refined.

There are five contact types in the Ansys Workbench: Bonded, No Separation, Frictionless, Rough, and Frictional, as seen in table 5. In this paper, the contact type is defined as Rough, and large deflection is turned on. In addition, to prevent penetration, the ‘Behavior’ is set to symmetric in Definition menu.

The finite element calculation results are shown in figure 11. From figures 11(a) to (c), it can be seen that for the same structure tube, the larger the helix angle is, the larger the maximum bending load, but the helix angle size of the multi-layer tube does not improve the bending performance of the structure significantly. As seen in figure 11(d), the more layers of the lightweight tube, the larger the maximum bending load the structure can

Table 6. Bending test data and bending lightweight factor.

| Types       | Types          | Mass (g) | Maximum compression load (N) | LWN-B (N g⁻¹) |
|-------------|----------------|----------|------------------------------|---------------|
| Single-layer tube | Test sample #1  | 108.37   | 1957.46                      | 18.06         |
|              | Test sample #2  | 106.53   | 1882.22                      | 17.67         |
|              | Test sample #3  | 108.92   | 1953.46                      | 17.93         |
|              | Simulation value| 107.26   | 1827.10                      | 17.03         |
| Double-layer tube | Test sample #1  | 109.66   | 3592.27                      | 32.76         |
|              | Test sample #2  | 108.49   | 3587.31                      | 33.07         |
|              | Test sample #3  | 107.58   | 3619.24                      | 33.64         |
|              | Simulation value| 107.37   | 3549.3                       | 33.06         |
| Three-layer tube | Test sample #1  | 109.83   | 4498.90                      | 40.96         |
|              | Test sample #2  | 107.26   | 4405.75                      | 41.08         |
|              | Test sample #3  | 109.42   | 4591.39                      | 41.96         |
|              | Simulation value| 108.64   | 4537.30                      | 41.77         |

Figure 11. Maximum compressive loads of different-layered variable-density structural tubes at different helix angles: (a) Single-layer tube; (b) Double-layer tube; (c) Three-layer tube; (d) Comparison of bionic tubes at each angle.
Therefore, the bending mechanical properties of the multi-layer tube are better than those of the single-layer tube structure.

To verify the effectiveness of the FEA, the TSE503B specific testing machine was used to conduct mechanical tests to determine the bending performance of the samples. Because the boundary conditions and mesh division are identical for all tubes during the simulation, only the single-layer 15°, double-layer 15°, and three-layer 15° tubes are compared in this paper. The test results and experimental device are shown in figure 12.

From table 6, it can be concluded that the maximum bending loads that can be withstood by the single-layer, double-layer and three-layer tubes were 1931.05 ± 42.33 N, 3599.61 ± 17.18 N, and 4498.68 ± 92.82 N, respectively, and the error compared with the finite element analysis results is less than 10%, indicating that the experimental results are basically consistent with the simulation results. Further calculations show that the bending lightweight factor (LWN-B) of the single-layer, double-layer, and three-layer tubes was 17.89 ± 0.20 N g⁻¹, 33.16 ± 0.45 N g⁻¹, 41.33 ± 0.55 N g⁻¹, respectively. The LWN-B by the three-layer tube was 2.31 times that of the single-layer tube, 1.25 times that of the double-layer tube, and approximately 1.85 times that of the single-layer tube. It can be seen that the LWN-B of the multi-layer tube was greatly improved relative to that of the single-layer tube.

Table 7. Technical parameters of DIT302A-TS.

| Parameter                              | Value          |
|----------------------------------------|----------------|
| Maximum impact energy (J)              | 300            |
| Maximum sample diameter (mm)           | 100            |
| Hammer lifting speed (m min⁻¹)         | 8.0            |
| Height measurement error (mm)          | ± 10           |
| Lift hammer height range (mm)          | 300–2000       |

Figure 12. Comparison of experimental and simulation results: (a) Single-layer tube; (b) Double-layer tube; (c) Three-layer tube; (d) Three-point bending experimental device.

withstand. Therefore, the bending mechanical properties of the multi-layer tube are better than those of the single-layer tube structure.
3.5. Energy absorption
To investigate the buffering energy absorption characteristics of the bionic structures, their impact resistance (single-layer 15°, double-layer 15°, and three-layer 15°) was determined using a drop-hammer impact testing machine (DIT302A-TS, Shenzhen Wance, China). The bionic structures were impacted from a set height with a certain mass and shape of hammer body. Then, the impact resistance of the samples was evaluated according to the experimental results obtained after the impact. Table 7 shows the drop-hammer impact testing machine and its technical parameters. Figures 12–14 show the force-displacement and energy-displacement curves of the different bionic lightweight tube samples.

Table 8 presents the data and related index calculations for the test samples during the impact. Table 9 shows a comparison of the impact resistances of the different bionic lightweight tubes, which indicates that the maximum peak force and average impact force of the double-layer tube were slightly larger than those of three-layer tube, followed by the single-layer tube. In general, the differences between the three structures were not significant. For energy absorption, the total and specific energy absorption of the three-layer tube were both approximately 10 times those of the single-layer tube, whereas those of the double-layer tube were approximately 8 times those of the single-layer tube, which showed that multiple layers could significantly improve the impact resistance of the structures. These results also verified that the multi-layer variable-density structure of the rostrum of the weevil could play a role in buffering energy absorption.

3.6. Multivariable and multi-objective parameter optimization design method based on response surface
In this paper, multi-objective parametric optimization of the bionic variable-density structures is performed using the response surface optimization module inside the ANSYS Workbench exploration design tool. A three-layer lightweight tube with a helix angle of 15° is used as the optimized design object, and the boundary and loading conditions comprise 6 degrees of freedom restricted at one end, and a pressure of 15 kN and a torque of 50 N·m applied at the other end. The optimization objective is to minimize the structural mass, maximum strain, and maximum deformation, and the constraint is that the maximum stress of the structure is less than the permissible stress. The mathematical model is as follows:
Table 8. Results of the impact test.

| Types       | Samples | Mass (g) | Impact distance (mm) | Maximum peak force (kN) | Total energy absorption (J) | Specific energy absorption (J kg⁻¹) | Average impact force (kN) |
|-------------|---------|----------|----------------------|-------------------------|-----------------------------|-----------------------------------|--------------------------|
| Single-layer| #1      | 109.21   | 7.50                 | 1.80                    | 3.49                        | 31.96                             | 0.4653                   |
|             | #2      | 108.62   | 8.49                 | 1.36                    | 4.21                        | 38.76                             | 0.4959                   |
|             | #3      | 108.58   | 7.52                 | 2.29                    | 3.06                        | 28.18                             | 0.4069                   |
| Double-layer| #1      | 109.13   | 27.00                | 1.89                    | 29.59                       | 271.14                            | 1.0959                   |
|             | #2      | 108.74   | 25.08                | 2.12                    | 29.11                       | 267.70                            | 1.1607                   |
|             | #3      | 108.95   | 27.20                | 1.96                    | 28.88                       | 265.08                            | 1.0618                   |
| Three-layer | #1      | 109.54   | 29.27                | 2.62                    | 33.57                       | 306.46                            | 1.1469                   |
|             | #2      | 108.11   | 40.51                | 1.49                    | 33.69                       | 311.63                            | 0.8316                   |
|             | #3      | 109.65   | 50.94                | 1.69                    | 37.32                       | 340.56                            | 0.7326                   |
Table 9. Comparison of buffer energy absorption of three types of bionic variable-density lightweight tubes.

| Types       | Impact distance (mm) | Maximum peak force (kN) | Total energy absorption (J) | Specific energy absorption (J/kg⁻¹) | Average impact force (kN) |
|-------------|----------------------|-------------------------|----------------------------|------------------------------------|--------------------------|
| Single-layer| 7.84 ± 0.57          | 1.82 ± 0.47             | 32.97 ± 5.36               | 0.46 ± 0.05                        | 1.41 ± 0.09              |
| Double-layer| 26.43 ± 1.17         | 1.99 ± 0.12             | 267.97 ± 3.04              | 1.11 ± 0.05                        | 1.81 ± 0.22              |
| Three-layer | 45.59 ± 10.84        | 1.812 ± 0.60            | 329.92 ± 18.26             | 0.82 ± 0.22                        | 1.89 ± 0.15              |
where $x_{i}^{(l)}$ is the lower limit of the design variables, $x_{i}^{(m)}$ is the upper limit of the design variables, $\sigma_{\text{max}}$ is the maximum stress, and $[\sigma]$ is the permissible stress.

Before optimizing the design, the bionic tube structure is first parametrically modeled and correlated with ANSYS. Six structural dimensions are selected as design variables, as shown in figure 16. To keep the inner and outer diameters, wall thickness, and porosity of the bionic tube constant, the variation range of each variable is determined to be ±10%, and the specific value range is shown in table 10.

The central composite sampling design method (Central Composite Design) is used, where the design-type selection is automatically defined, and the program finds the optimal type based on the sample points. The range of each design variable is the constraint, so that 45 sample points of 6 design variables are extracted. After the simulation, the mass, stress, deformation value, and strain of each sample point can be found. Based on the calculated simulation results of the sample points, the response surfaces (RSs) of the design variables and the target function can be obtained, so that the relationship between the structural parameters and the target value can be revealed. Figure 17 represents the relationship between the helix angle of each layer in the multi-layer tube and the equivalent strain and maximum deformation of the structure.

From figures 17–18, the effect of any two design variables on the objective function can be seen with the remaining design variables held constant. From figures 17(a)–(c), it can be seen that the maximum value of strain occurs at the two limit positions of the helix angle, and the minimum value is located approximately in the middle of the range. From figures 17(d)–(f), it can be seen that the larger the first (A1)- and third (A3)-layer helix angles, the larger the maximum deformation of the structure, whereas the smaller the second-layer helix angle (A2), the larger the maximum deformation of the structure. As seen in figure 18, the strain is smaller when the value of the width of the helix angle of each layer is located in the middle position of the range, whereas the larger the width, the smaller the deformation. Therefore, determining the optimal point requires weighing each objective function to finally obtain the optimal solution.
Figure 15. Three-layer tube impact force-displacement curves and energy-displacement curves: (a) Sample 1; (b) Sample 2; (c) Sample 3.

Figure 16. Design variables and dimensional parameters.

Table 10. Design variable constraints.

| Design Variables | Initial Value | Lower limit | Upper limit |
|------------------|---------------|-------------|-------------|
| A1 (°)           | 15°           | 10°         | 20°         |
| A2 (°)           | 15°           | 10°         | 20°         |
| A3 (°)           | 15°           | 10°         | 20°         |
| W1 (mm)          | 1.9           | 1.71        | 2.09        |
| W2 (mm)          | 1.9           | 1.71        | 2.09        |
| W3 (mm)          | 1.9           | 1.71        | 2.09        |
On the basis of response surface, 6000 samples were taken by the screening method (Screening), and then the optimal solution was found by a multi-objective genetic optimization algorithm, so that three groups of alternative solutions were identified, as shown in Table 11.

In our variance analysis, $R^2$, adjusted $R^2$ ($R_{adj}^2$), and root mean square error (RMSE) are used to evaluate the fitting accuracy, which can be calculated as follows:

$$R^2 = 1 - \frac{SSE}{SST}$$

$$RMSE = \sqrt{\frac{SSE}{M - p - 1}}$$

$$R_{adj}^2 = 1 - (1 - R^2) \frac{M - 1}{M - p - 1}$$

$$F = \frac{(SST - SSE)/p}{SSE/(M - p - 1)}$$

where $p$ is the number of non-constant terms in the RS model, $M$ is the number of sample points, and SSE and SST are the sum of squared errors and the total sum of squares, respectively, which are calculated as follows:

$$SSE = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$

$$SST = \sum_{i=1}^{n} (y_i - \bar{y})^2$$

where $y_i$ represents the FEA result, $\hat{y}_i$ denotes the RS approximation value, and $\bar{y}$ is the mean value of the FEA results, $y_i$.

From Tables 11 and 12, it can be seen that all three solutions are better than the original solution and can effectively reduce the mass and equivalent strain of the samples. Because optimized solution I has the lowest mass and strain, it is considered the optimal solution. The p value of each response surface model is less than 0.0001, indicating that the response surface model is extremely significant. In terms of precision inspection, $R^2$
Figure 18. Response surfaces of helix angle width, equivalent strain, and maximum deformation: (a) W1-W2, equivalent strain; (b) W1-W3, equivalent strain; (c) W2-W3, equivalent strain; (d) W1-W2, maximum deformation; (e) W1-W3, maximum deformation; (f) W2-W3, maximum deformation.

Table 11. Optimization scheme based on objective function.

|                | Optimization Solutions I | Optimization Solutions II | Optimization Solutions III |
|----------------|---------------------------|---------------------------|---------------------------|
| A1             | 13.49°                    | 13.70°                    | 14.37°                    |
| A2             | 15.55°                    | 15.40°                    | 15.96°                    |
| A3             | 10.12°                    | 10.18°                    | 10.22°                    |
| W1             | 1.8799                    | 1.8724                    | 1.8602                    |
| W2             | 1.8679                    | 1.9155                    | 1.9343                    |
| W3             | 1.8703                    | 1.8585                    | 1.825                     |
| Maximum stress (MPa) | 25.614                  | 25.501                    | 25.64                     |
| Maximum Deformation (mm) | 1.2723                  | 1.2705                    | 1.2714                    |
| Mass (kg)      | 0.10458                   | 0.10473                   | 0.1046                    |
| Maximum strain | 0.01659                   | 0.016627                  | 0.016975                  |

Table 12. Performance comparison between the original and optimized solutions.

|                | Original Solution | Optimization Solutions I | Optimization Solutions II | Optimization Solutions III |
|----------------|-------------------|---------------------------|---------------------------|---------------------------|
| Maximum Stress (MPa) | 31.78              | 25.614                    | 25.501                    | 25.64                     |
|                 |                   | −19.4%                    | −19.76%                   | −19.32%                   |
| Maximum Deformation (mm) | 1.32             | 1.2723                    | 1.2705                    | 1.2714                    |
|                 |                   | −3.61%                    | −3.75%                    | −3.68%                    |
| Mass (kg)      | 0.1054            | 0.10458                   | 0.10473                   | 0.1046                    |
|                 |                   | −0.78%                    | −0.64%                    | −0.76%                    |
| Maximum strain | 0.0216            | 0.01659                   | 0.016627                  | 0.016975                  |
|                 |                   | −23.19%                   | −23.02%                   | −21.41%                   |

(Note: In Table 12, ‘−’ represents a percentage reduction compared to the original solution.)
and $R^2_{adj}$ are all greater than 0.97, indicating that the response surface model has a high fitting accuracy and can meet the accuracy requirements of parameter optimization of the proposed structure. The error measures of the RS for shape optimization are listed in Table 13. The maximum relative errors are within 5% (Figure 19), which indicates the good accuracies of these RS models.

### 4. Conclusions

In this study, bionic variable-density lightweight structures inspired by the rostrum of *Cyrtotrachelus buqueti* Guer are proposed, and their mechanical properties are investigated via simulations and experiments. The proposed three-layer lightweight tube with a helix angle of 15° was optimized using the response surface method. Within the limitations of the study, the following conclusions can be drawn:

(1) Under the action of compression load, when the inner and outer diameters, wall thickness, and porosity of the bionic lightweight tube structures are the same, the more layers of the tube, the greater the compressive capacity and compression lightweight coefficient. When the number of layers is the same, the maximum compressive load that the structure can withstand gradually decreases with the increase of helix angle. However, when the helix angle is greater than or equal to 40°, the maximum compression load borne by the three lightweight tube structures remains basically the same.

(2) For all tube types (i.e., single-layer, double-layer, and three-layer), the maximum torsional load increases and then decreases as the helix angle increases. Likewise, as the number of layers increases, the torsional load and torsional lightweight factor increase.

(3) When the number of layers is the same, the greater the helix angle of the lightweight tube, the greater the maximum bending load the structure can withstand, and the more layers, the less obvious the helix angle is in performance enhancement. The more layers, the greater the maximum bending load and bending lightweight factor the structure can withstand.

(4) The more layers of a lightweight tube, the better its buffer energy absorption performance. The experimental results showed that under the same conditions, the total energy absorption and specific energy absorption of the three-layer lightweight tube were approximately 10 times those of the single-layer tube.

### Table 13. Error measures of the RS for shape optimization.

|                | $R^2$  | $R^2_{adj}$ | RMSE |
|----------------|--------|-------------|------|
| Maximum Stress | 0.9926 | 0.9806      | 0.1946 |
| Mass           | 0.9935 | 0.9886      | 0.1967 |
| Maximum Deformation | 0.9869 | 0.9713      | 0.1862 |
| Maximum strain | 0.9933 | 0.9882      | 0.1952 |

Figure 19. Relative errors of response surface function.

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(5) A response surface-based optimization method is proposed for the parametric optimization design of the bionic multi-layer tubes to achieve the mass minimization, deformation, and maximum strain of the structure under the condition of satisfying the working conditions.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Conflict of interests

The authors declare that there is no conflict of interest regarding the publication of this article.

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