DOI: 10.23977/analc.2025.040102
ISSN 2616-1958 Vol. 4 Num. 1

Mechanical properties of beetle elytra and biomimetic structures: a review

Kaixiao Huang[a], Yuhang Shi[b], Wei Wu[c,*]

School of Mechanical Engineering, University of Shanghai for Science and Technology, Jun Gong Road, Shanghai, China

[a]2635984266@qq.com, [b]1944217146@qq.com, [c]weiwuxst@163.com

**Corresponding author*

Keywords: Beetle elytron, Mechanical properties, Bionics, Structural design

Abstract: The elytra of beetles are natural bio-composite materials, exhibiting exceptional mechanical properties attributed to their intricate microstructures, which play vital roles in protection and flight facilitation. This review systematically gives the macro- and nano-scale mechanical behaviours of beetle elytra, including tensile strength, flexural resistance, and environmental influences such as moisture content and tanning processes. Mechanical testing methods, such as tensile and three-point bending tests, show species-specific structural adaptations. Nanomechanical analyses reveal the impact of hydration and enzymatic activity on elastic modulus and hardness. Biomimetic applications inspired by microstructures, such as sandwich honeycomb models, hollow column arrays, and double-tube thin-walled designs, demonstrate significant advancements in lightweight, high-strength engineering materials. This review consolidates current research to guide future innovations in bioinspired material design, emphasizing the synergy between natural microarchitectures and engineering applications.

1. Introduction

The hardened forewings of beetle elytra serve as a quintessential example of natural biomaterials optimized through millions of years of evolution. As an important natural biomaterial, they exhibit exceptional mechanical properties, not only a critical role in protecting the insect's body from external damage but also significantly enhancing flight efficiency by reducing aerodynamic drag. The unique structural features of beetle elytra, such as the combination of a rigid outer shell and a flexible inner layer, enable them to demonstrate superior mechanical characteristics, including compressive resistance, tensile strength, and toughness, even in complex environments [1-3]. In recent years, significant progress has been made in the research on the mechanical properties of beetle elytra, particularly in understanding the relationship between microstructure and macroscopic performance [4,5].

The internal structure of beetle elytra encompasses a diverse array of microarchitectures, including honeycomb structures, laminated plywood-like hollow structures supported by small columns, stacked layers and channel structures formed by filamentous fibres, and porous foam structures [6-9]. Researchers have leveraged these intricate microstructures to design various biomimetic structures, which have found applications in practical engineering [10]. This review summarizes the factors influencing the macroscopic mechanical behaviour and microscopic mechanical properties of beetle elytra and introduces current research directions in biomimicry inspired by the structural design of beetle elytra.

2. Micromechanical properties of beetle elytra

Beetle elytra are a bio composite material. In order to explore its mechanical properties, it is necessary to carry out mechanical tests, and the macroscopic mechanical test methods mainly include tensile tests and three-point bending tests [11].

The dung beetle (*Copris ochus* Motschulsky) lives in soil for extended periods, and its body surface exhibits a regular distribution of depressions and bumps, which make it difficult to adhere to the soil, while also demonstrating excellent wear resistance, as shown in Figure 1a and Figure 1b [12]. In the tensile test, the yield strength of the beetle elytra is 17.12 ± 3.55 N, the maximum tensile strength is 14.74 ± 4.11 N, the yield strength is 1.4 ± 0.15 GPa, the tensile strength is 1.2 ± 0.21 GPa, and the elastic modulus is 14.56 ± 4.20 GPa. The plasticity index is 0.241 ± 0.10, and the tensile elongation ranges from 12.1% to 36.3%, as shown in Figure 1d. As seen from the cross-sectional microstructure of the elytra after tensile fracture, the elytra are a criss-cross stacked multi-layer structure, with each layer composed of fibre filaments made of chitin and protein, as shown in Figure 1c. The staggered stacking structure makes the elytra difficult to pull apart, giving it strong tensile strength, while the fibre filaments provide the elytra with good ductility.

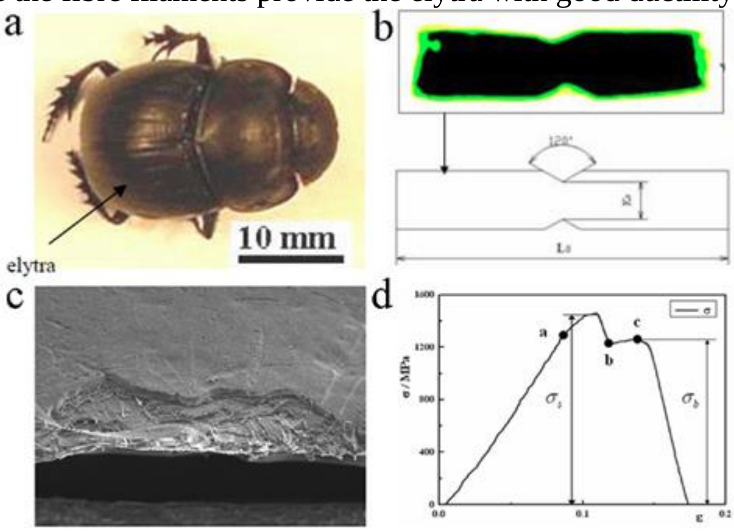

Figure 1: (a) Tensile specimen of the dung beetle (*Copris ochus* Motschulsky) and (b) its elytra; (c) Broken elytra and its cross-sectional microstructure after stretching; (d) Tensile test results [12].

The male stag beetle (*Lucanus cervus*) exhibits a large body size and aggressive behavior, which contributes to the development of highly pressure-resistant elytra, as shown in Figure 2 [13]. Studies have revealed that the exocuticle and endocuticle of the elytra exhibit a multi-layered architecture with varying thicknesses, while the lower section comprises a hollow structure reinforced by trabeculae. In this research, three-point bending tests and finite element simulations have been conducted to examine the mechanical behaviour of the elytra under two distinct loading conditions: normal conditions (when the elytra naturally cover the beetle's body) and abnormal conditions (when the elytra are laid flat). The results of transverse and longitudinal three-point bending tests indicate that the elytra do not exhibit anisotropic properties. Under normal conditions, the flexural strength is measured at 222 ± 172 MPa and the flexural modulus is 811 ± 650 MPa. In contrast, under abnormal conditions, the flexural strength decreases to 73 ± 39 MPa and the flexural modulus decreases to 455 ± 287 MPa. These findings suggest that the internal microstructure of the elytra is optimally arranged to maximize its mechanical performance when in its natural position on the beetle's body, thereby enhancing its compressive resistance.

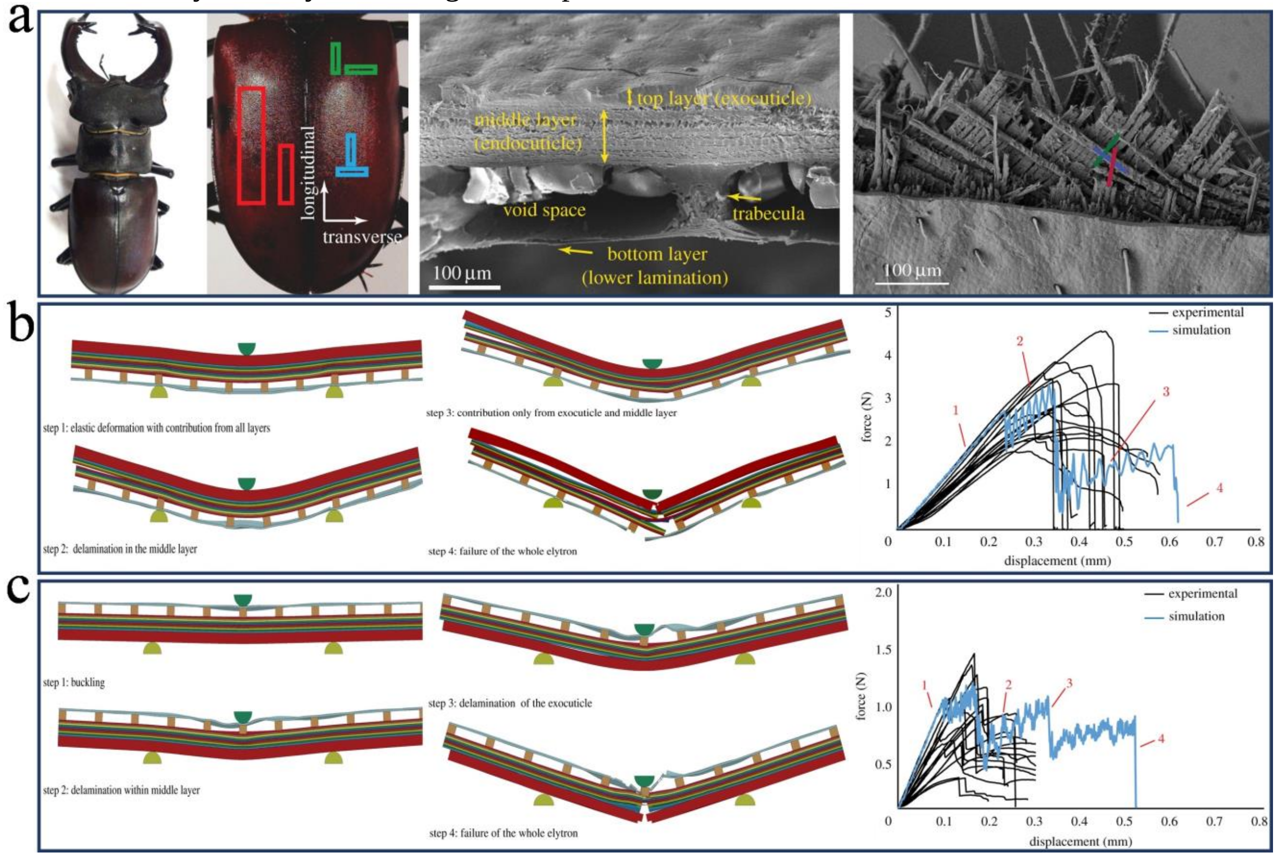

Figure 2: (a) Male stag beetle (*Lucanus cervus*) and the microstructure of cross-section; (b) Three-point bending test results of the elytra under normal conditions; (c) Three-point bending test results of the elytra under abnormal conditions [13].

3. Nanomechanical properties of beetle elytra

Macroscopic mechanical testing methods can obtain the mechanical properties of the entire elytra. However, some beetle elytra are thin and small with complex structures. The internal structures are most at the micrometre or even nanometre scale. It is necessary to summarize microscopic mechanical property researches of elytra.

The nanomechanical properties of beetle elytra are influenced by their moisture content. Specifically, the elastic modulus and hardness of hydrated elytra are lower compared to those in a dry state [14]. After removing the elytra from the dung beetle, nanomechanical tests are conducted at intervals of 0.5 hours, 1 hour, 48 hours, 96 hours, and 5 months. As the placement time increased, the internal moisture content of the elytra decreases, leading to a corresponding increase in both elastic modulus and hardness (Figure 3). This trend indicates that as moisture decreases, the cross-linking between chitin and protein becomes tighter, resulting in higher elastic modulus and hardness values.

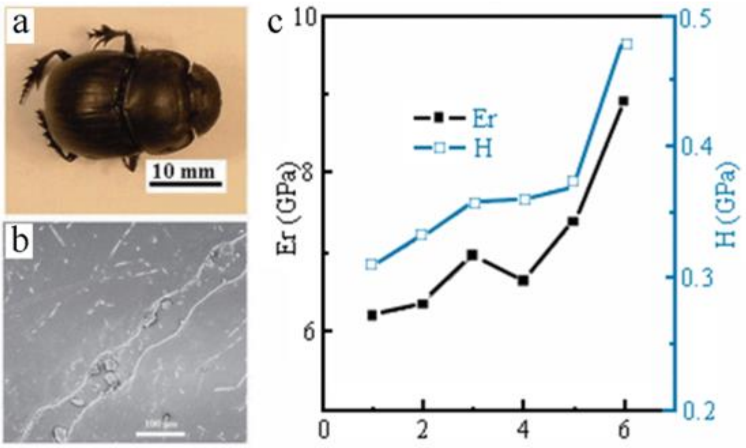

Figure 3: (a) Dung beetle; (b) Microstructure of the elytra surface; (c) Changes in elastic modulus and hardness of the elytra at different moisture contents [14].

The nanomechanical properties of beetle elytra are also influenced by their genetic makeup and the degree of tanning. During the early stages of tanning, the nanomechanical properties of *Tenebrio molitor* and *Tribolium castaneum* show only minimal differences [15]. However, as the tanning process advances and the levels of laccase and aspartate decarboxylase in their bodies change, the storage modulus of the two species exhibit significant differences at various tanning stages (Figure 4). Different beetle species possess distinct genes that regulate the expression of laccase and aspartate decarboxylase. The levels of these enzymes influence the extent of chitin-protein cross-linking during the tanning process of the elytra, which directly affects both the degree of tanning and the mechanical properties of the elytra. Consequently, the levels of laccase and aspartate decarboxylase in the bodies play a crucial role in determining the nanomechanical properties of the elytra post-tanning.

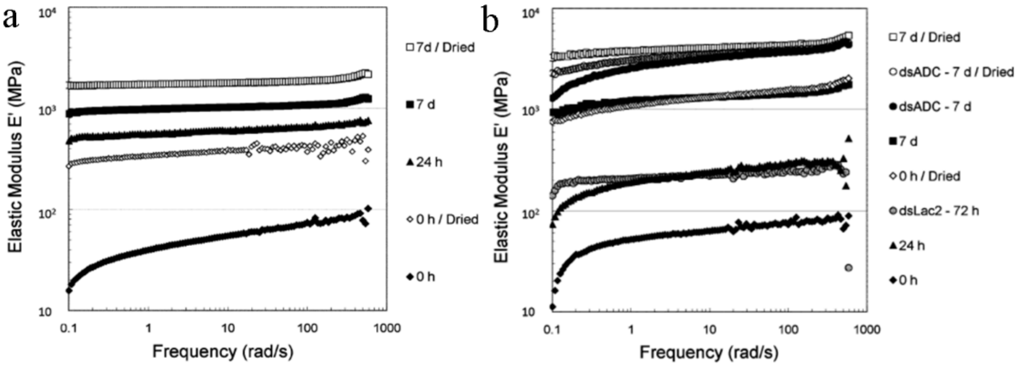

Figure 4: Storage modulus of (a) *Tenebrio molitor* and (b) *Tribolium castaneum* at varying tanning degrees [15].

The nanomechanical properties of beetle elytra differ depending on whether the beetles live in water, on land, or underground, and they also vary with position on the elytra [16]. The *Cybister tripunctatus* beetle is an amphibious species capable of swimming in water and flying from water to land. *Scarabaeus sacer* lives underground, while *Holotrichia titanis* and *Protaetia brevitarsis* are small-sized, tree-dwelling flying beetles, and *Allomyrina dichotoma* is a large-sized tree-dwelling flying beetle. The Young's modulus and hardness of the elytra of flying beetles are higher than those of land beetles (Figure 5a). The Young's modulus and hardness vary at different positions on the elytra of beetles with different living habits. The Young's modulus and hardness are smallest at the centre of the elytra of the five beetles, while the values at other positions show irregular differences (Figure 5b).

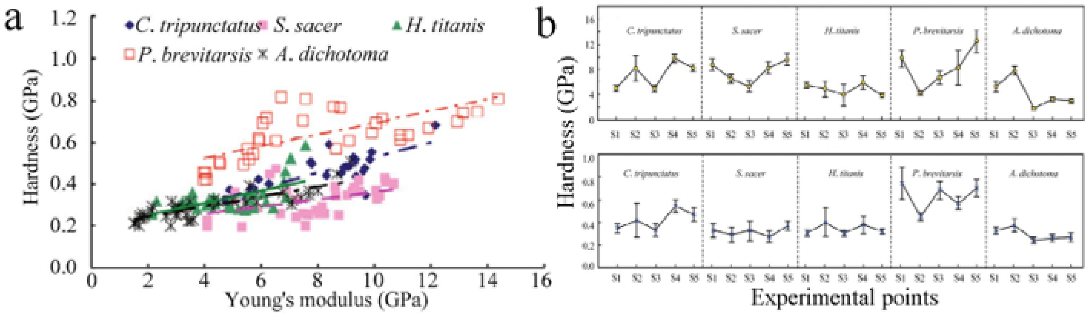

Figure 5: Comparison of mechanical properties of beetle elytra in five different living environments [16].

The nanomechanical properties of beetle elytra exhibit variability across different positions in their cross-sections, and there are notable differences in the mechanical properties between distinct colour regions [17]. For *Harmonia axyridis*, both the black spots and orange areas possess a dense multi-layered microstructure. The black regions of the elytra demonstrate higher elastic modulus and hardness compared to the orange regions. Specifically, within the orange areas, the elastic modulus and hardness progressively increase from the outer epidermis to the inner epidermis, whereas in the black spots, these properties gradually decrease from the outer to the inner layers (Figure 6). The presence of pigmentation, particularly melanin, significantly influences the mechanical properties of the elytra, with melanin-rich areas exhibiting greater elastic modulus and hardness.

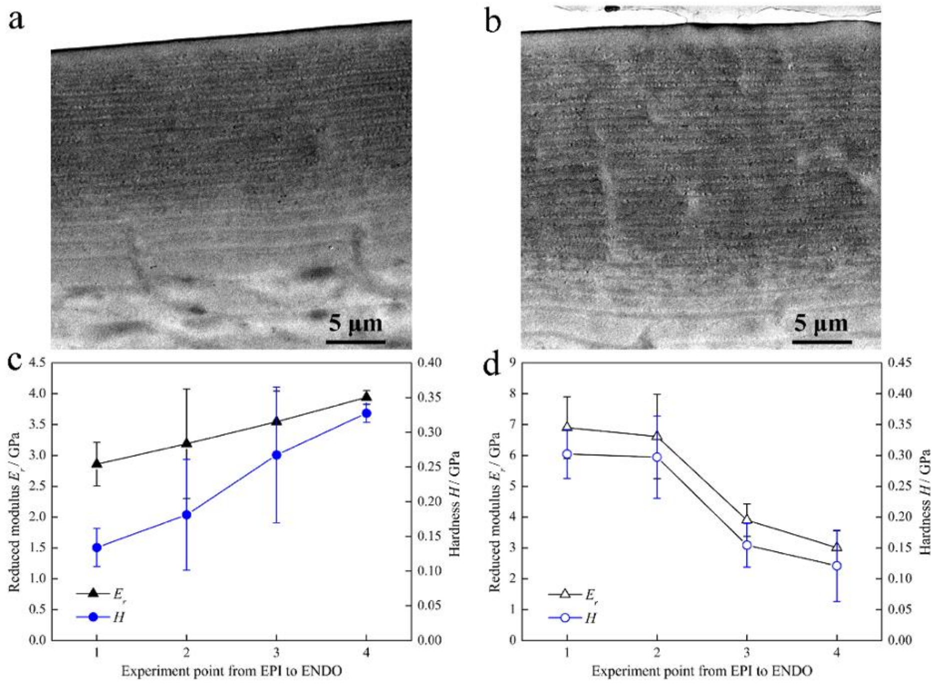

Figure 6: Cross-sectional microstructure of (a) the orange region and (b) the black spot region of the elytra of *Harmonia axyridis*; Variations in elastic modulus and hardness from the outer to inner epidermis in (c) the orange region and (d) the black spot region of the elytra [17].

4. Biomimetic structures of beetle elytra

Researches on the mechanical properties of beetle elytra have revealed that these structures exhibit lightweight and high-strength characteristics. These properties are not only influenced by the composition of the biological materials but are also closely linked to their intricate internal microstructure. Consequently, a variety of biomimetic lightweight and high-strength structures and materials, inspired by beetle elytra, have been developed for application in engineering fields.

The internal structures and lightweight yet high-strength characteristics of the elytra of *Allomyrina dichotoma* beetle were investigated [18-23]. The study revealed fibrous protein pillars within the cuticle, where the fibres form layers that interconnect the upper and lower layers, with the pillars sandwiched between them, forming a structure similar to a sandwich honeycomb. Based on these findings, beetle elytra-inspired structural models (BEPs) and conventional honeycomb structural models (HPs) were developed and fabricated. Comparative compression tests revealed that the compressive strength and energy absorption capacity of the BEPs structure were 2.44 times and 5 times higher than those of the HPs structure, respectively. The bending resistance of BEPs and HPs structures with the same thickness was compared. The bending strength of the BEPs structure was 42% higher than that of the HPs structure. It can be known that the internal sandwich honeycomb structure layout similar to that of the beetle elytra has higher compressive and bending resistance than the ordinary sandwich honeycomb structure. The bending resistance of BEPs and HPs structures with the same thickness was compared. The bending strength of the BEPs structure was 42% higher than that of the HPs structure. It can be concluded that the internal sandwich honeycomb structure layout similar to that of the beetle elytra has higher compressive and bending resistance than the ordinary sandwich honeycomb structure.

The elytra of the *Cybister tripunctatus* beetle also have a hollow structure supported by small columns inside [24]. The cavities and hollow bridge pier-like structures in the elytra are the main reasons for its lightweight nature. To study the influence of its microstructure on strength, three structural models (I, II, and III) have been established. Structural model I is designed based on the microstructure of the elytra, consisting of long through-holes and hollow columns arranged perpendicularly. Structural model II is composed of hollow spheres and hollow columns arranged alternately. Structural model III is made up of a honeycomb network structure. Samples are 3D printed using acrylonitrile butadiene styrene and subjected to compression tests and three-point bending tests. In the compression tests, the stiffness values for structural models I, II, and III are 5.09×10^7 N/m, 6.08×10^7 N/m, and 4.54×10^7 N/m, respectively, with corresponding compressive strengths of 13.78 MPa, 15.91 MPa, and 14.93 MPa. In the three-point bending tests, the bending stiffness for all three models is 5.09×10^7 N/m, while their bending strengths ware 16.35 MPa, 27.25 MPa, and 13.62 MPa, respectively. The test results indicate that all three bionic structures exhibit lightweight and high-strength characteristics. Notably, structure model II most closely resembles the internal microstructure of the beetle's elytra. Materials fabricated according to this model demonstrate the highest stiffness and specific stiffness, as well as superior deformation resistance.

The elytra of *Harmonia axyridis* possess internal cavities and small column structures. These small columns are composed of thin-walled tubules, with some columns interconnected with the thin-walled layer [25]. Based on this microstructure, six bionic double-tube thin-walled structural models have been designed. The outer tubes have triangular, quadrilateral, pentagonal, hexagonal, heptagonal, and circular cross-sections, while all inner tubes are circular. All six models share the same tube wall thickness. Compression mechanical simulations are conducted on these models to investigate the crushing force required and the energy absorbed at various compression depths. Each model is subjected to compressions of 30 mm, 60 mm, 90 mm, 120 mm, and 140 mm. The results indicate that the heptagonal and circular models required higher crushing forces, whereas the triangular, heptagonal, and circular models absorb more energy. Tube structures with different shapes are arranged into regular and irregular configurations in the elytra-inspired structural models. When subjected to identical surface pressures, the regularly arranged models demonstrate superior energy absorption and exhibited enhanced resistance to deformation and collapse.

Based on the structural characteristics of the elytra of the beetles *Leptinotarsa decemlineata* and *Cassida viridis*, a lightweight and high-strength building structure module unit has been designed, and a bionic house has been built in using this module unit [26]. The module unit is composed of hollow beams and columns smoothly connected with double shell layers. In regions with lower loads, sparse trabeculae are distributed within the space formed by fine, network-like structures, and long and dense small beams are located between the double-shell layers, increasing the structural depth between the double-shell layers and facilitating the transmission of force between the upper and lower shell layers. The module units are assembled into the shape of the beetle elytra. This bionic house is lightweight, has high compressive strength, and occupies a small area.

5. Conclusions

The mechanical properties of beetle elytra, shaped by their evolutionary adaptations and intricate hierarchical microstructures, offer profound insights for biomimetic material design. Nano and macro mechanical analyses demonstrate how environmental factors—such as moisture content, enzymatic activity during tanning, and melanin distribution—directly modulate elastic modulus and hardness, underscoring the dynamic interplay between material composition and mechanical performance. Biomimetic applications inspired by these natural designs, including sandwich honeycomb models, hollow column arrays, and double-tube thin-walled structures, exhibit remarkable advancements in engineering.

Acknowledgements

This work was supported by Shanghai Sailing Program (No. 22YF1429800) and National Natural Science Foundation of China (No. 52205314).

References

[1] Linz, D.M., Hu, A.W., Sitvarin, M.I. (2016) Functional value of elytra under various stresses in the red flour beetle. Tribolium castaneum. Sci Rep, 6: 34813.

[2] Tuyen, Q.L., Tien, V.T., Hieu, T.T. (2014) How could beetle's elytra support their own weight during forward flight? J Bionic Eng; 11: 529–540.

[3] Chen, J.X., Zu, Q., Wu, G. (2015) Review of beetle forewing structures and their biomimetic applications in China: (II) On the three-dimensional structure, modeling and imitation. Mater Sci Eng C; 55: 620–633

[4] Yu, X., Zhang, X., Chen, J. (2020) The flexural property and its synergistic mechanism of multibody molded beetle elytron plates.Science China Technological Sciences, 63(5):1-9.

[5] Xu, M., Pan, L., Chen, J. (2019) The flexural properties of end-trabecular beetle elytron plates and their flexural failure mechanism. J Mater Sci 54, 8414–8425.

[6] Zhang, Z., Chen, J., Elbashiry, E.M., Guo, Z., Yu, X. (2019). Effects of changes in the structural parameters of bionic straw sandwich concrete beetle elytron plates on their mechanical and thermal insulation properties. Journal of the mechanical behavior of biomedical materials, 90, 217-225.

[7] Zhang, X., Yu, X., Chen, J. (2020) Vibration properties and transverse shear characteristics of multibody molded beetle elytron plates. Sci. China Technol. Sci. 63, 2584–2592.

[8] Chen, J., Hao, N., Pan, L. (2020) Characteristics of compressive mechanical properties and strengthening mechanism of 3D-printed grid beetle elytron plates. J Mater Sci 55, 8541–8552.

[9] Chen, J., Tuo, W., Guo, Z., Yan, L. (2017). The 3D lightweight structural characteristics of the beetle forewing. Materials science & engineering. C, Materials for biological applications, 71, 1347-1351.

[10] Saurav, D., Anna, S. (2023) Bio-logic, a review on the biomimetic application in architectural and structural design, Ain Shams Engineering Journal, 14(1), 101822.
[11] Sun, J.Y., Bhushan, B. (2012) Structure and mechanical properties of beetle wings: a review. RSC Advances, 2(33), 12606-12623.
[12] Sun, J.Y., Tong, J., Chen, D.H. (2010) Micro-tensile testing of the lightweight laminated structures of beetle elytra cuticle. Advances in Natural Science, 3(2), 225-234.
[13] Kundanati, L., Signetti, S., Gupta, H.S. (2018) Multilayer stag beetle elytra perform better under external loading via nonsymmetric bending properties. Journal of the Royal Society Interfaace, 15(144), 20180427.
[14] Zhang, Z.J., Wu, W., Sun, J.Y. (2015) Investigation of water's effect on nanomechanical characteristics of beetle cuticle, International Conference on Manipulation, Manufacturing and Measurement on the Nanoscale. New York: Institute of Electrical and Electronics Engineers Inc, 10,5-9.
[15] Lomakin, J., Huber, P.A., Eichler, C. (2011) Mechanical properties of the beetle elytron, a biological composite material. Biomacromolecules, 12(2), 321-335.
[16] Yu, M., Hermann, I., Dai, Z.D. (2013) Mechanical and frictional properties of the elytra of five species of beetles. Journal of Bionic Engineering, 10(1), 77-83.
[17] Sun, J.Y, Wu, W., Du, R.J. (2017) Nanomechanical properties of elytra derived from irreversible and reversible color-changing beetles, International Conference on Manipulation, Manufacturing and Measurement on the Nanoscale. New York: Institute of Electrical and Electronics Engineers Inc, 7,7-11.
[18] Zhang, X.M., Xie, J., Chen, J.X. (2017) The beetle elytron plate: a lightweight, high-strength and buffering functional-structural bionic material. Scientific Reports, 7(1), 4440.
[19] Zhang, X.M., Chen, J.X., Okabe, Y. (2020) Influence of honeycomb dimensions and forming methods on the compressive properties of beetle elytron plates. Journal of Sandwich Structures and Materials, 22(1), 28-39.
[20] Yu, X.D., Pan, L.C., Chen, J.X. (2019) Experimental and numerical study on the energy absorption abilities of trabecular–honeycomb biomimetic structures inspired by beetle elytra. Journal of Materials Science, 54(3), 2193-2204.
[21] Chen, J.X., Wu, G. (2013) Beetle forewings: Epitome of the optimal design for lightweight composite materials. Carbohydrate Polymers, 91(2), 659-665.
[22] Chen, J.X., Zhang, X.M., Okabe, Y.(2019)Beetle elytron plate and the synergistic mechanism of a trabecular-honeycomb core structure. Science China Technological Sciences, 62(1), 87-93.
[23] Chen, J.X., Zhang, X.M., Okabe, Y.(2017) The deformation mode and strengthening mechanism of compression in the beetle elytron plate. Materials and Design, 131, 481-486.
[24] Guo, C., Li, D., Lu, Z.Y.(2014) Mechanical properties of a novel, lightweight structure inspired by beetle’s elytra. Chinese Science Bulletin, 59(26), 3341-3347.
[25] Xiang, J.W., Du, J.X., Li, D.C.(2017) Numerical analysis of the impact resistance in aluminum alloy bi-tubular thin-walled structures designs inspired by beetle elytra. Journal of Materials Science, 52(22), 13247-13260.
[26] Kamp, T.V.D, Dörstelmann, M., Rolo, T.D.S. (2015) Beetle elytra as role models for lightweight building construction. Entomologie Heute, 27, 149-158.