Engineering Structures 265 (2022) 114490

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Dynamic behaviors of bio-inspired structures: Design, mechanisms, and models

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ARTICLE INFO

Keywords:
Bio-inspired structures
Dynamic behaviors
Impact resistance
Energy absorption

ABSTRACT

Following nature's design principles, biological materials have evolved highly efficient and multifunctional structures to maximally utilize available materials and structures to survive in harsh environments. Biomaterials and bio-systems with lightweight and high impact-resistant features attract tremendous attention due to their fascinating architecture design strategies (e.g., structural hierarchy, gradient design, and thin-walled tubular/cellular structure). Here, we provide an overview of various biological systems with sophisticated architecture to resist impact and enhance energy absorption, including woodpecker, mantis shrimp, bone, nacre, mussel shell, horn, turtle shell, and bamboo. From a perspective of biological functions, comprehensive understanding of the structure-function relationship in superior impact-resistance and energy absorption capability is critical. The dynamic behaviors of bio-inspired structures are reviewed from the design, mechanisms, and models, integrating the key insights. Results demonstrate that representative bio-inspired structures exhibit up to 60 J/g for specific energy absorption, showing excellent potential for engineering applications. Discussions on current challenges, directions, and future possible data-driven modeling in engineering design and the development of low-cost manufacturing technologies may enable the possible engineering applications of bio-inspired structures.

1. Introduction

Over billions of years of evolution, natural structures have been honed for multifunctionality from atomic to macro scales. For example, lightweight, high strength and toughness, offering new insights into designing synthetic structures with superior mechanical properties [1–9]. Common structural motifs originating from biological materials/systems include tubular (e.g., beetle elytra [10], horse hooves [11,12], and horns [13]), fibrous (e.g., spider silk [14], silkworm cocoon [15], and wood [16,17]), gradient (e.g., teeth [18]), cellular (e.g., bone and muscles [19,20]), hierarchical (e.g., fractal tree leaf [21], Euplectella aspergillum skeleton [22] and conch shell [23–25]), helical (e.g., dactyl club [26] and glass sponge [27]), and suture structures (e.g., armadillo [28]). "Minimizing material while maximizing performance" is the clear way of how creatures survive in harsh environments. Designs as "seasoned professionals", nature always gives rise to structural designs and achieves complex well-organized architecture to perform various functions to probably survive (as more damage-tolerant) than individual components. Hence, natural materials exhibit far greater structural and mechanical properties relative to their constituents. During the fierce combat, biological systems have evolved capabilities to withstand impact loading with maximal efficiency, multi-directional loading, and low-to-medium (up to 50 m/s) [29] velocity. For example, the impact velocity of mantis shrimp dactyl club can

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https://doi.org/10.1016/j.engstruct.2022.114490
Received 3 January 2022; Received in revised form 25 May 2022; Accepted 28 May 2022
Available online 13 June 2022

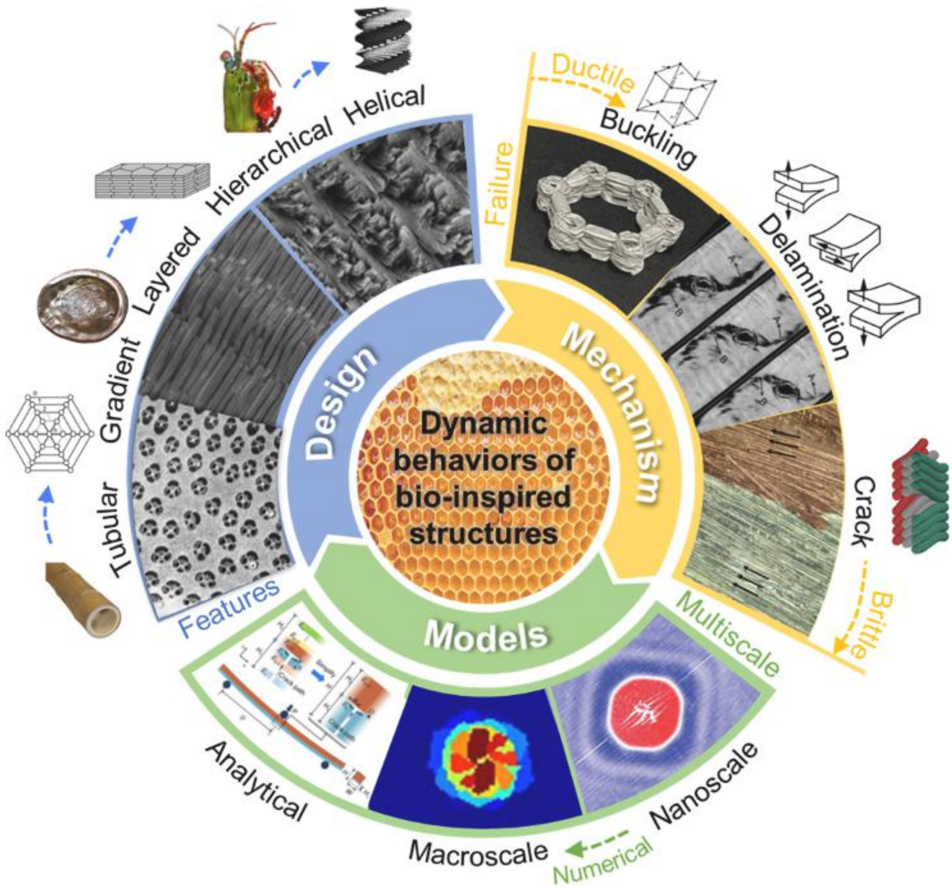

Fig. 1. Overview of dynamic behaviors of bio-inspired structures [4–6]. Bio-inspired designs usually include common biological structural design elements such as tubular, gradient, layered, hierarchical, and helical. Bio-inspired structures exhibit different deformation modes and failure mechanisms from ductile failure (e.g., buckling, delamination) to brittle fracture. Various models, including analytical, numerical and multiscale modeling frameworks, have been developed to comprehensively understand the dynamic behaviors of bio-inspired structures.

rate 23 m/s when smashing the deadly mechanism, attributable to the saddle-shaped spiral of the delicate microscopic architecture [30]. For those which are subject to impact load (up to 30 m/s), the tubular architecture effectively arrests cracks while dampening stress waves, opening for engineering structures and the functional materials [31,32]. Moreover, found in many natural materials (e.g., the alligator [33], armor [34], woodpecker beak [35], and human mandible [36]), the evolutionary process of biological functions [37]. Beyond biological function, comprehensive understanding of the dynamic structural behaviors of impact-resistant bio-inspired structures is and their efficient energy absorption in applications [38–45].

In this paper, we review the recent progress and reveal the "structure-performance" relationship of bio-inspired dynamic structures across nano-, micro- and macro-scales (Fig. 1). Incorporating structural elements (i.e., tubular, gradient, layered, helical, overlapping, etc.), mechanical behaviors summarized, representative species/biological structures. Bio-inspired structures for impact-resistance, energy absorption, woodpecker beak, mantis shrimp, nacre, bamboo, lobster, honeycomb, bio-inspired concepts ... tailored, overlapping ... dynamic behaviors and mechanisms ... may provide ... designing structures ... enable ... possible ... engineering structures ... should ... interplay of the dynamic behaviors of biological systems and bio-inspired structures ... mechanics perspective ... the biological functions ... such as self-healing ... the mechanism currently in view.

2. Representative biological systems and bio-inspired designs

2.1. Beetle-inspired structures

Beetle's straight-up ... the forewing ... lightweight ... protective ... external load (e.g., the impact force up to 23 N [57]). Based on the experimental observations of their internal laminated structures (Fig. 2(a)) ... regular ... interactions ... the trabecular [58–60]. More specifically, ... cross-section ... rectangular structure ... trabeculae ... middle lamination (Fig. 2(b)). Meanwhile, the fibers ... through the trabecular (pillar) structures (Fig. 2(c)), with inter-laminar ... approximately 30 ... [61]. Also, spiral ... structures can be observed ... trabecular ... volume, respectively [62].

With a comprehensive understanding of the internal microstructures of beetle's forewing, various bio-inspired structures with energy-absorbing performance have been proposed and investigated (Fig. 2(d)). For example, Hao et al. [63] designed bio-inspired energy-absorbing structures ... Meanwhile, ... beetle ... honeycomb structure ... self-similar structure ... the wall [53,64]. Conventional ... (Fig. 2(d)). The improved energy absorption ability ... attributed mainly ...

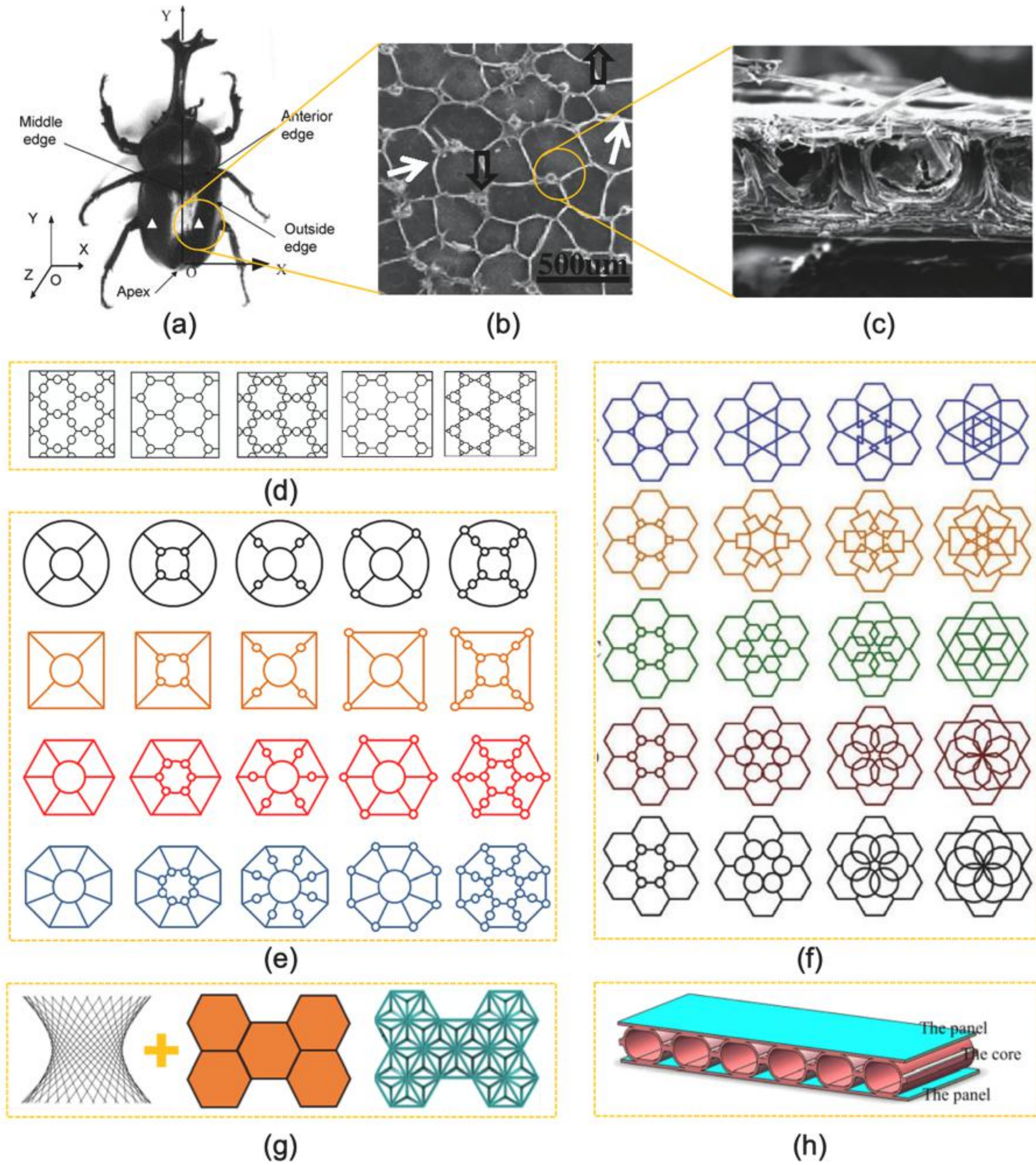

Fig. 2. Microstructure of the beetle elytra and the corresponding bio-inspired structures. (a) Adult beetle Allomyrina dichotoma [61]. (b) Cross-section of the beetle elytra [69]. (c) The trabecular structure [70]. (d) Beetle elytra-inspired honeycomb thin-walled structure [62,64]. (e) Beetle elytra-inspired multi-cell tubular structures for energy absorption [66]. (f) Bionic tubes with a figure based on the internal structure of beetle elytra [67]. (g) A crashworthy structure inspired by the beetle's forewing [71]. (h) Beetle elytra-inspired sandwich structure with circular cavities [72].

the bio-inspired structure with ribs, via the extrusion forming of each [68]. Based on a constitutive model with different strain-rate and thermal theory, a beetle-elytra-inspired model ... Considering regular and irregular stiffened plates, analysis of the topological configuration of the bio-structure, Xie et al. [65] proposed evaluating the energy dissipation by plastic deformation in both numerical optimization of the bio-inspired thin-walled tubes under axial and bending deformations for outstanding energy absorption. Beyond the hierarchical order, Zhang et al. [73] demonstrated

Inspired by the hierarchical scheme of tubular structures with both the sub-circular and thickness designs, significantly varying sizes of beetle elytra, Du et al. [66] designed multi-cell tubes which showed superior performances than the hierarchical tubular structures with different topology, and further optimized the parameters of the structural ratio of the tubes including circular, quadrangular, hexagonal, through multi-objective optimization methodology octagonal shapes (Fig. 2(e)). By analogy, topology ... Moreover, Yu et al. [74] created a novel interlocked ... to explore the hexagonal form ... honeycomb (Fig. 2(f)) [67]. An analytical model was also used to ... energy developed based on Simplified Super Folding Element (SSFE) theory ... absorption performance to validate the finite element (FE) model of bionic multi-cell tubes. In addition to axial loadings,

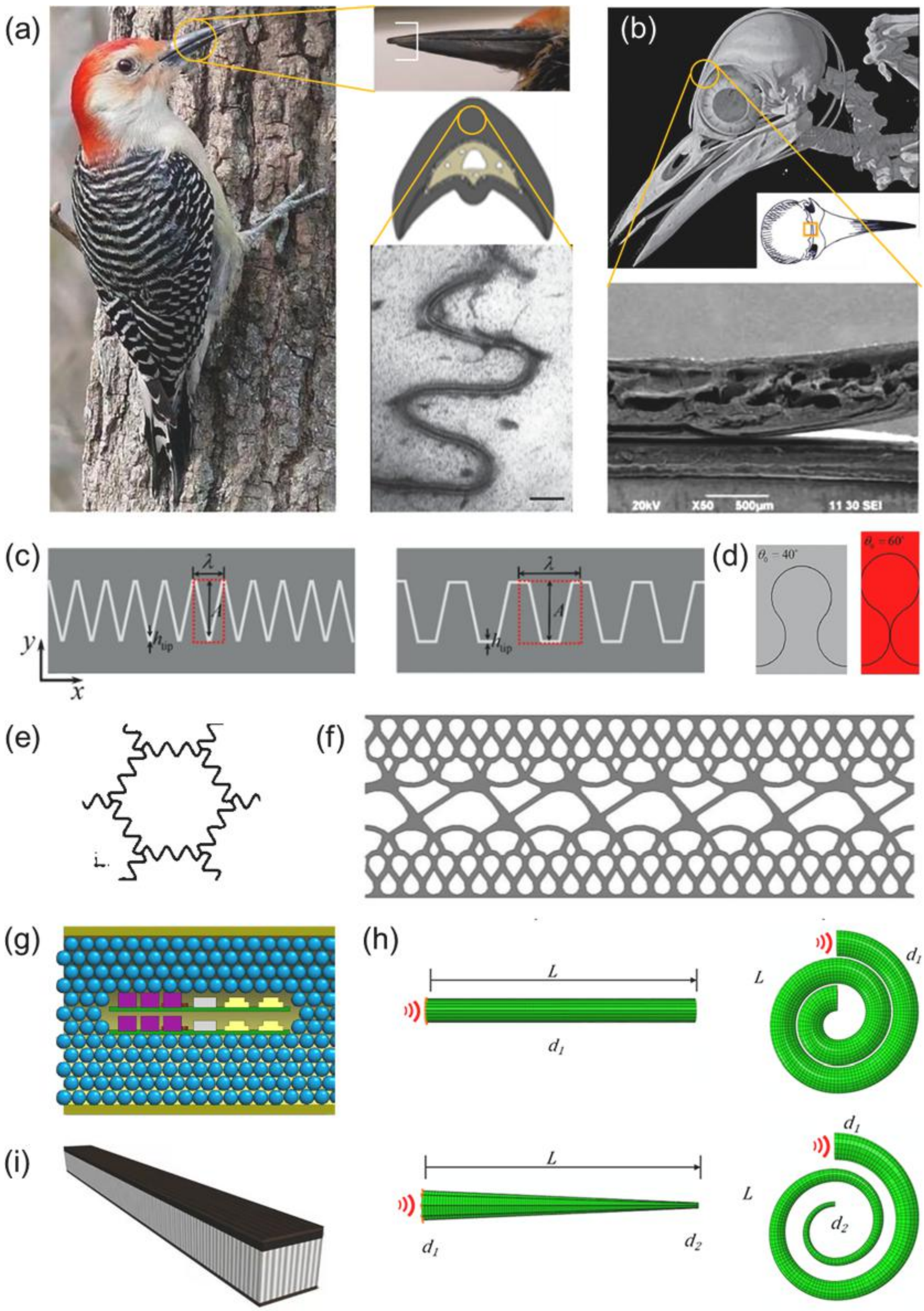

Fig. 3. (a) A male red-bellied woodpecker and the wavy nanostructure of woodpecker's beak [35]; (b) Skull of the Golden-fronted woodpecker (Melanerpes aurifrons) and the microstructure of woodpecker's beak [17,18,91]; (c) Bio-inspired composites with sutures [92]; (d) Bio-inspired "jigsaw"-like interlocking structures [93]; (e) Woodpecker's beak-inspired wavy honeycomb structure [94]; (f) Cellular structures [95]; (g) Shock absorber [96] inspired by the sponge bone of woodpecker's skull; (h) Woodpecker hyoid-inspired spiral structure for mitigating transmitted stress waves [36]; (i) Sandwich beam inspired by the structural feature of woodpecker's beak [97]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Xu et al. [75] explored the flexural property of the trabecular-based sandwich designs (Fig. 3(h)). Moreover, recently, sandwich structures have been tubular structures made of 3D-printing material and obtained an extended multi-layer configuration with optimal energy storage ... ability ... Wang et al. [71] developed a sort of performance-oriented two-layer bio-inspired three-dimensional ... microscopic ... sandwich structure [76] configuration ... re-entrant honeycomb pattern (Fig. 3(g)). Considering the cyclic structure formed by neighboring ... the light weight energy-absorption ... Meng et al. [72] proposed a fabricated sandwich structure with ... cavities ... in-plane ...

2.2. Woodpecker-inspired structures

Woodpecker exhibits exceptional impact performance ... When the pecker performs the hammering motion with the beak (Fig. 5(a))

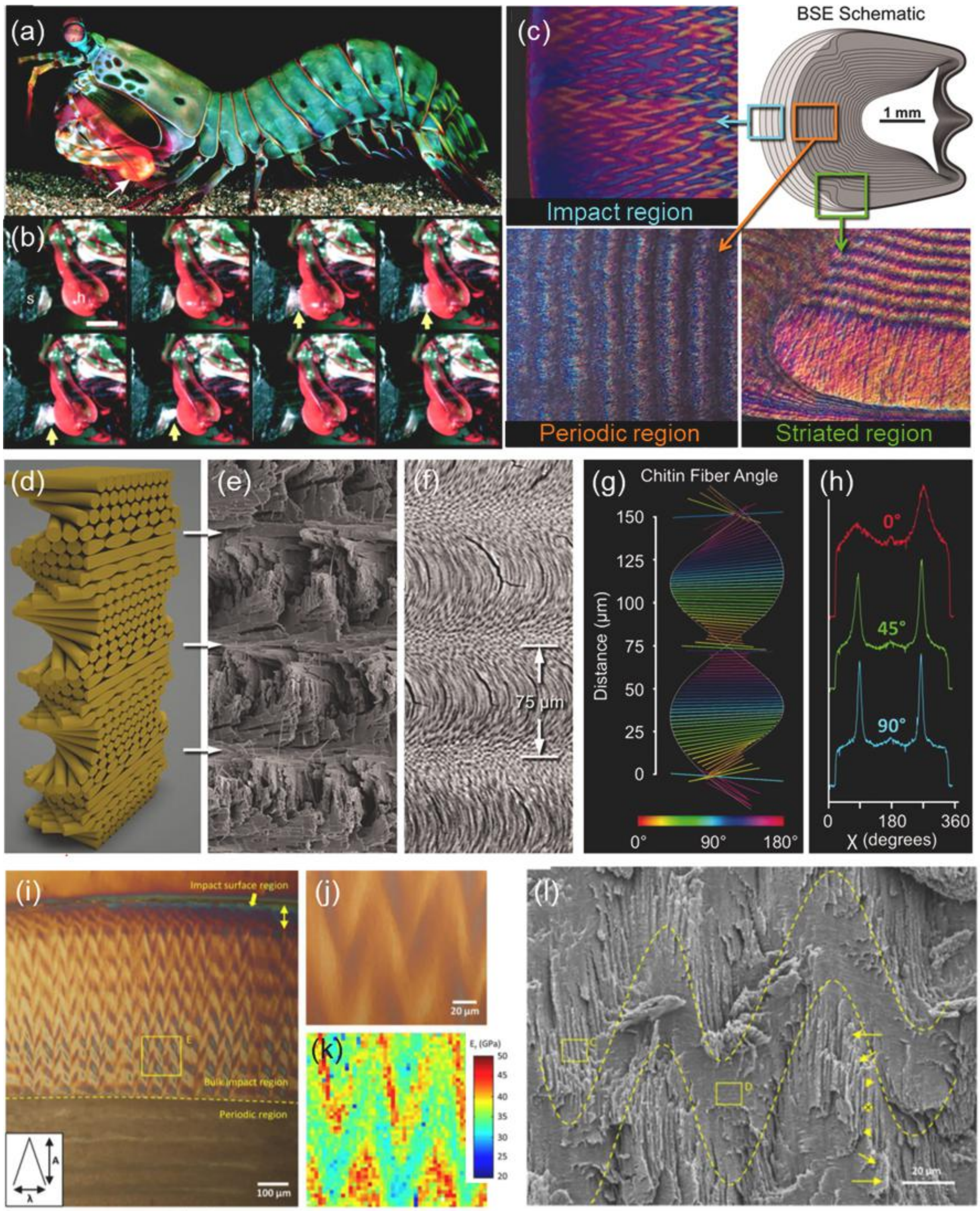

Fig. 4. (a) The peacock mantis shrimp [105]; (b) How a peacock mantis shrimp uses its hammer to strike a snail [30, 106]; (c) Optical micrograph of the impact region, periodic region, and striated region [109]; (d) A generalized helicoidal architecture [109]; (e) SEM fractograph and (f) polished surface of the helicoidal structure within the periodic region [109]; (g) The chitin fiber orientation ... X-ray ... (h) three representative χ plots of the α-chitin (110) reflection [109]; (i) Higher-magnification ... of the impact region; (j) ... (k) The corresponding modulus map; (l) ... microstructure ... [112].

[77]. The pecking frequency can reach 18–22 times per second and 12,000 times a day on average, while every bout takes around 50 ms [78]. During the pecking cycle, the impact deceleration is approximately in the order of 1000 g with a repeated impact speed of around 6–7 m/s, yet no head injury is observed after the impact [79–81]. Thus, the investigation on the mechanism of the woodpecker's head injury resistance has attracted wide attention worldwide, and most research focused on the unique anatomical characteristics of the woodpecker (Fig. 6(a) and (b)).

Avian beaks are representative biotic composites with unique mechanical properties (e.g., elastic modulus and strength), which closely link to their biological function. The upper beak of the woodpecker directly contacts the tree trunk, which is critical for the impact mitigation [82]. According to the multiscale observations of a red-bellied woodpecker beak, Lee et al. [35] found that the woodpecker beak has a hierarchical structure consisting of the rhamphotheca (the outer part), foam (middle layer), and bony (inner layer), among which the foam layer is composed of [illegible] (Fig. [illegible]) bundles of collagen [83], possesses a flexible graded porous structure to accommodate its biological requirements. Specifically, the porosity of the foam layer is about 50–65% and 27–30% at the middle and near the interfaces, respectively, between the foam layer and rhamphotheca/bony layers, which require higher strength to resist the severe localized contact failure. Meanwhile, the most robust woodpecker skulls show a tight-packed wavy configuration [illegible] along the edge (i.e., suture structures) [illegible] (Fig. 6(a)), which may contribute to the remarkable impact-resistant tolerance.

Another dispensable part for resisting impact injuries is the woodpecker's hyoid apparatus [illegible], which is composed of [illegible] [78,81,84]. Notably, the hyoid apparatus is composed of cartilage and bones [illegible] through the tongue [illegible] encompasses woodpecker's head [80,85]. [illegible] structure of the hyoid apparatus converts the stress waves [86], yielding deformation, [illegible] the strain energy is dissipated [illegible] elastic behavior. Meanwhile, proper positioning of the skull and the skull structural design significantly contribute to the impact mitigation [87]. Compared to birds with comparable weight (e.g., the Mongolian skylark), a woodpecker contains more plate-like trabecular bone, [illegible] the skull, [illegible] higher [illegible] ultimate [illegible] impact-resistance [88]. Furthermore, [illegible] during pecking, [illegible] directed to the [illegible] the woodpecker's skull [illegible] external impact [84,89,90].

Inspired by the structure of woodpecker, Yu et al. [92] proposed a woodpecker-inspired [illegible] performance (Fig. 6(c)), which has a systematic [illegible] Malek et al. [93] comprehensively studied a "wire-like" [illegible] structure (Fig. 6(d)) [illegible] the woodpecker's hyoid [illegible] the thick [illegible] woodpecker's [illegible] numerically [illegible] energy absorption [illegible] slowly convert or absorb the impact energy.

Based on the wavy structure of the woodpecker beak, Ha et al. [94] proposed a wavy honeycomb (Fig. 6(e)) and explored the structural durability by manipulating the wave number and amplitude; the superior energy absorption performance was achieved in contrast to the conventional ones, which [illegible] a panel with the core of hexagonal honeycomb. Moreover, a machine learning algorithm was also used to aid the design process by estimating the compressive performance of the wavy honeycomb with different geometric parameters and material properties, i.e., wave number, wave amplitude, cell size, wall thickness and material type (i.e., aluminum, Nomex, carbon fiber, and glass) [99]).

In addition, a compliant mechanism-based design strategy with topology optimization was used to obtain the energy dissipation mechanism of woodpecker's pecking (Fig. 6(f)) [95]. From the perspective of material, Yu et al. [96] designed a spongy bone-inspired composite composed of close-packed glass (Fig. 6(g)) in order to protect the microelectronic devices under high-g military [illegible]. Compared with conventional shock isolation structure, the [illegible] woodpecker-inspired device successfully passed the shock survivability [illegible] under extreme loading up to 60,000 g of firing tests [illegible] of the device. The underlying mechanism for effective shock isolation is due to the absorption of high-frequency mechanical excitation (especially those close to the resonance frequency of the microelectronic devices) [illegible] transmitted. Moreover, [illegible] et al. [86] explored the geometric effect of hyoid bone-inspired [illegible] on stress wave propagation (Fig. 6(h)), where the [illegible] geometries effectively achieved impact mitigation.

Given the integrated effect of different parts in woodpecker's head, Abo Sabah et al. [97,100,101] developed bio-inspired sandwich beam (Fig. 6(i)) that comprised of carbon fiber reinforced polymer (CFRP) laminated layer (with high strength), rubber layer (for spreading and absorbing impact energy), aluminum honeycomb (with [illegible] light weight structure), and CFRP layer (for [illegible] structural integrity). Mimicking the beak, hyoid, spongy bone, and skull of a woodpecker, [illegible] the geometric effect of these [illegible] dual-scale [illegible] impact performance [102].

2.3. Mantis shrimp-inspired structures

Mantis shrimp (Crustacea: Stomatopoda, Fig. 4(a)) use their large raptorial appendages (also known as smashers) to defend against predators [illegible] [103,104] [illegible] impact-resistant [illegible] dactyl clubs, [illegible] [105]. Using the [illegible] bulbous heel of the dactyl, they can smash [illegible] hard-shelled and soft-bodied (e.g., snail) [illegible] extreme [illegible] from a unique power amplification mechanism (Fig. 4(b)) [30]. Namely, a spring-latch [illegible] the elastic energy generated during muscle contraction [illegible] released [illegible] attack [106,107]. Notably, the peacock mantis shrimp (Odontodactylus scyllarus) is capable of generating accelerations of 10^5 m/s^2 and impact speed of over 20 m/s, which is regarded as one of the most powerful impact scenarios in nature [30]. In addition, comparative studies on [illegible] 15 mantis shrimp species (including [illegible] smashing and spearing appendages) [illegible] the impact mechanics [illegible] smasher [illegible] fundamental [illegible] (i.e., [illegible]) [108].

Recent investigations [illegible] performance [illegible] mantis shrimp [illegible] structures (Fig. 4(c)) [illegible] consisting of the [illegible]

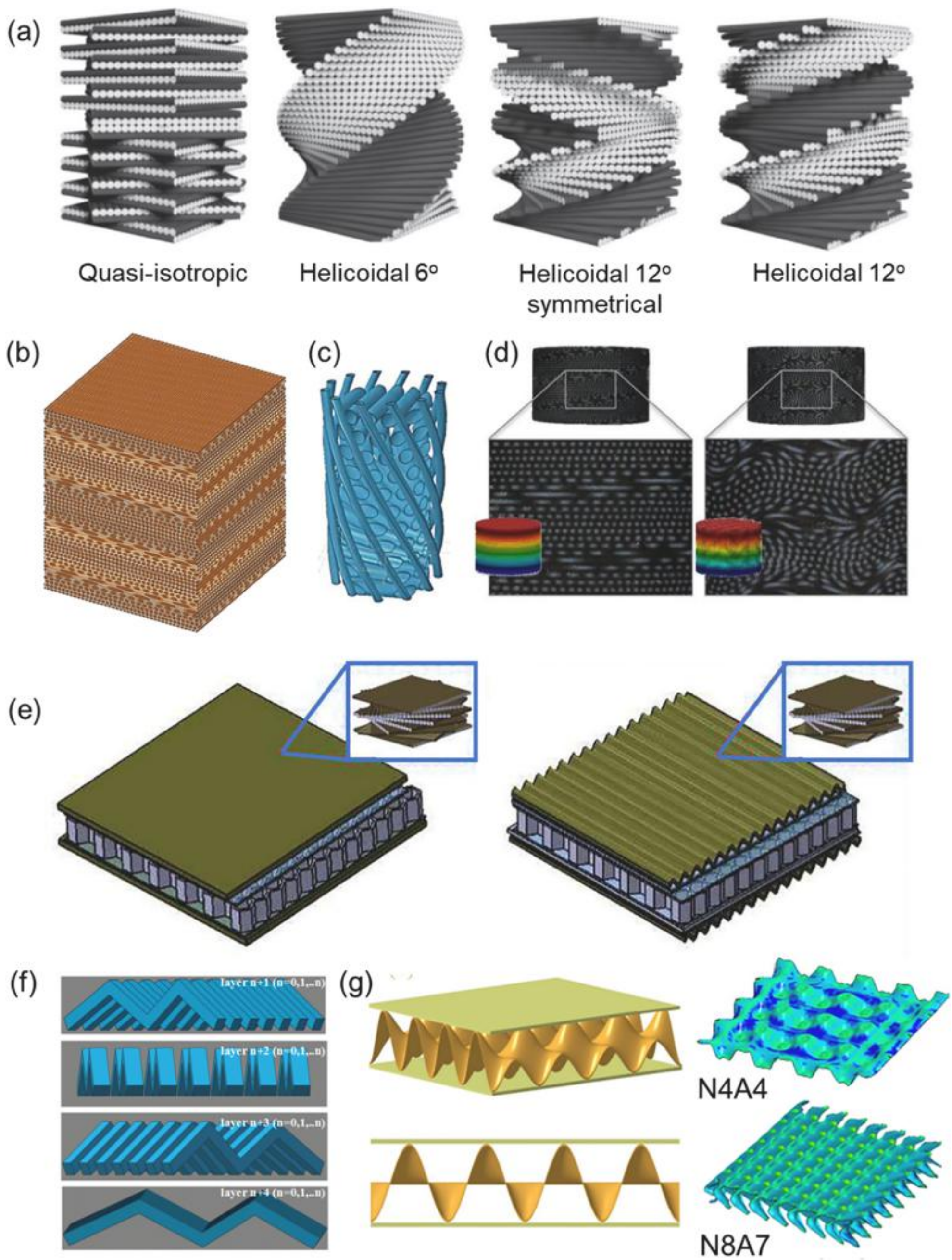

Fig. 5. (a) Quasi-isotropic and bio-inspired helicoidal laminates [48]; (b) Schematic of helicoidal fibre layers in bio-inspired impact-resistant composites [47]; (c) Helicoidal fibre structures [115]; (d) 3D printed helicoidal and herringbone bio-composites [112]; (e) Dactyl-inspired sandwich honeycomb with a flat table [117]; (f) A simplified herringbone-modified helicoidal architecture [118] inspired by the impact region of the dactyl club; (g) Bi-directional sinusoidal corrugated sandwich structure and the deformation of structures with different wave numbers (N) and amplitudes (A) [119].

dactyl) across [110]. From a cross-sectional view, the whole of the mantis shrimp club is divided into three representative regions, including the highly mineralized impact region, the central periodic region, and the striated region, with more organic-inorganic periodic composition (Fig. 4(c)) [109].

Synthetically, the chitin fibrils are helicoidally organized (also called the Bouligand arrangement) in the periodic region, where the chitin fibers stack up along with a twisted staggered angle (Fig. 4(d)-(f)) and the corresponding orientation of chitin fibers is highly related to the expanded helicoidal period (Fig. 4(g)-(h)) [109]. Various experiments studies have revealed that the periodic region predominantly contributes the energy dissipation capability via helicoidal fibrils (i.e., strain-hardening [110,111], crack deflection twisting from the distinctly helicoidal fibrils [112]) and the shear-stress filtering effect of the transverse strain [113].

A closer examination of the impact region from a different interface orientation shows that there exists a skeleton with highly ordered herringbone pattern with identical wavelength observable (Fig. 4(i)) [112]. Similarly, the energy impact mechanism of the impact region also stems from the crack deflection twist [109,114]. To probe the mechanical properties (e.g., elastic modulus and hardness) of the subject, Yaraghi et al. [112] carried out nanoindentation experiments on the herringbone region (Fig. 4(j)), manifesting that the local mechanical properties directly relate to the herringbone pattern (Fig. 4(k)). Furthermore, the scanning electron microscopy (SEM) observation (Fig. 4(l)) further analyzed the fibers found in the highly compacted impact regions, and they contribute to explain the image. When subjected to impact loading, the organic fibers within the shear-stressed matrix act to stop crack propagation again, and the organic matrix further restricts crack propagation by creating a tortuous interface [104].

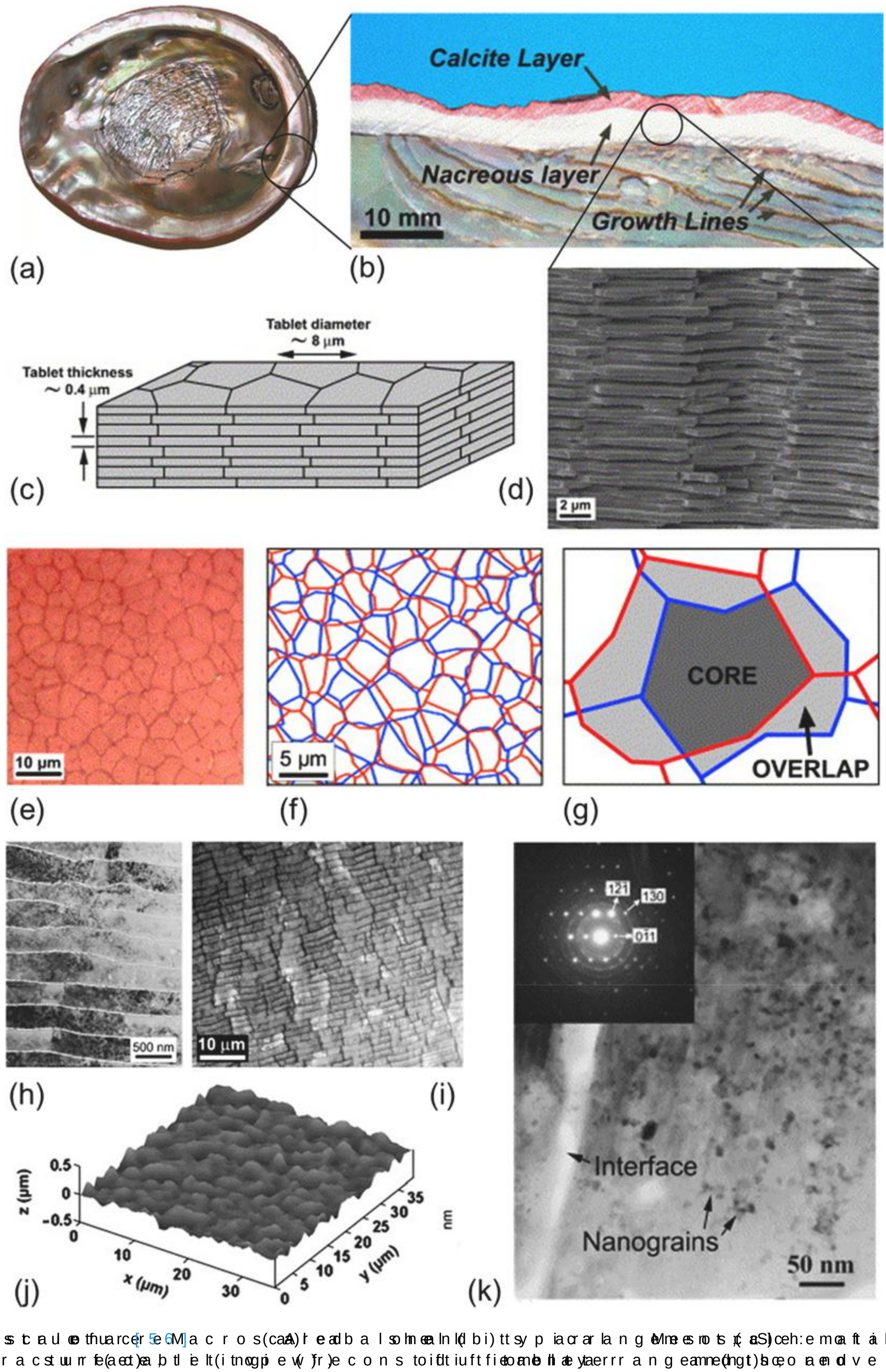

Fig. 6. Multiscale structure of nacre [56]: Macrostructure: (a) red abalone shell, (b) its typical arrangement; Mesostructure: (c) schematic of tablet arrangement, SEM figure of fracture surface (d), tablet tiling (top view) (e), reconstitution of the tablet arrangement (f), (g) the core and several overlap arrangements in macro; Microstructure: (h) TEM micrographs showing tablet waviness, (i) optical photographs of layered structure of fresh water mussel Lampsilis Cardium; (j) topology of the layer based on a profilometer; Nanostructure: (k) TEM graph of a nacre tablet with nanograins. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

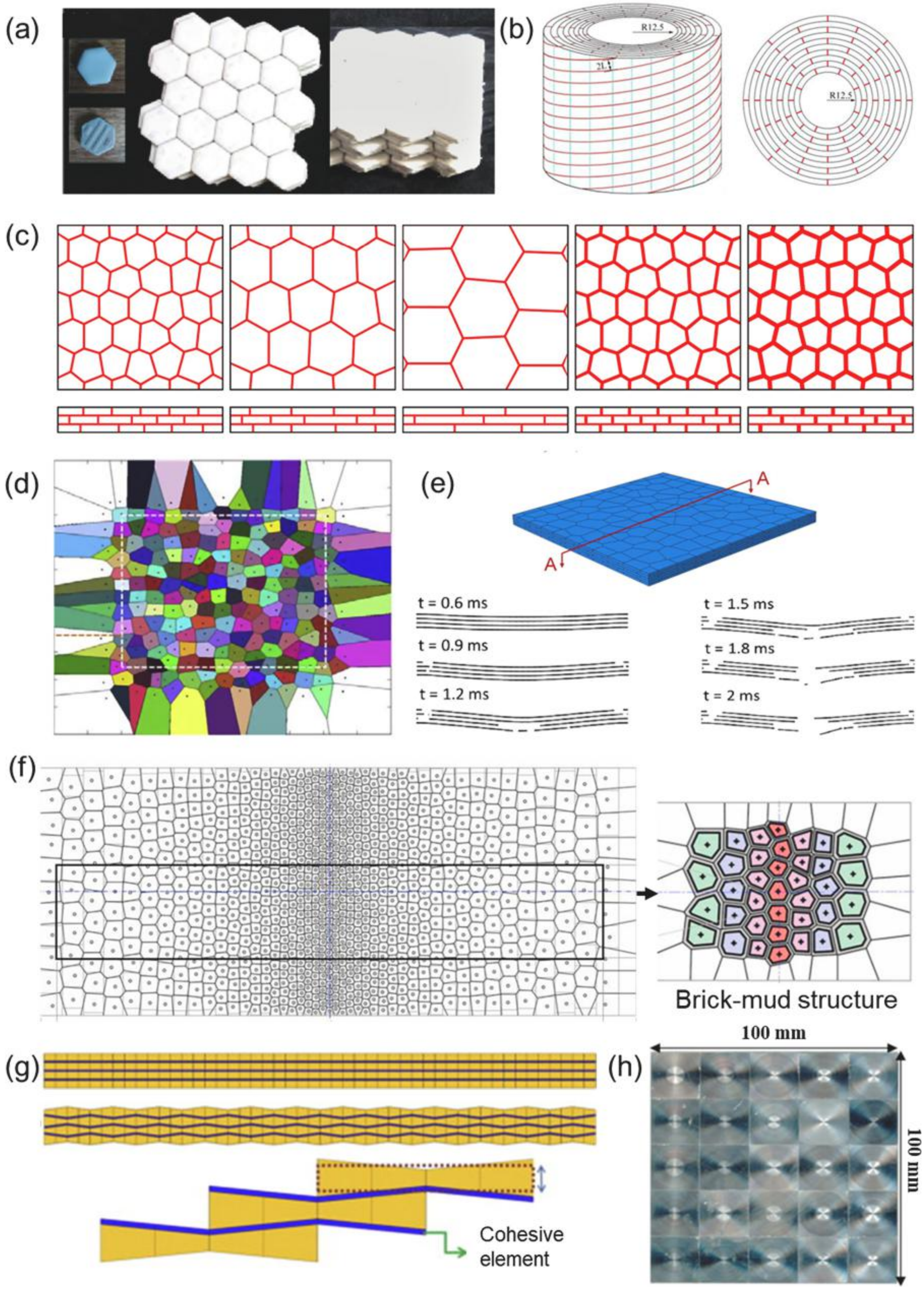

Fig. 7. (a) Nacre-inspired composites with layered staggered structure [132]; (b) Bio-inspired CFRP tube based on the discontinuous interdigitated architecture [136]; (c) Nacre-like composites with various geometric properties generated by 3D printing [137]; (d) Voronoi-polygonal mimicking nacre structure; (e) the snapshots of crack propagation under impulsive loading [138]; (f) Gradient nacre-like brick-mud structure [140]; (g) Nacre-inspired composites with waviness [145]; (h) Nacre-like aluminium (AA7075-T651) plate to study the impact performance [142].

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2.4. Nacre-inspired structures

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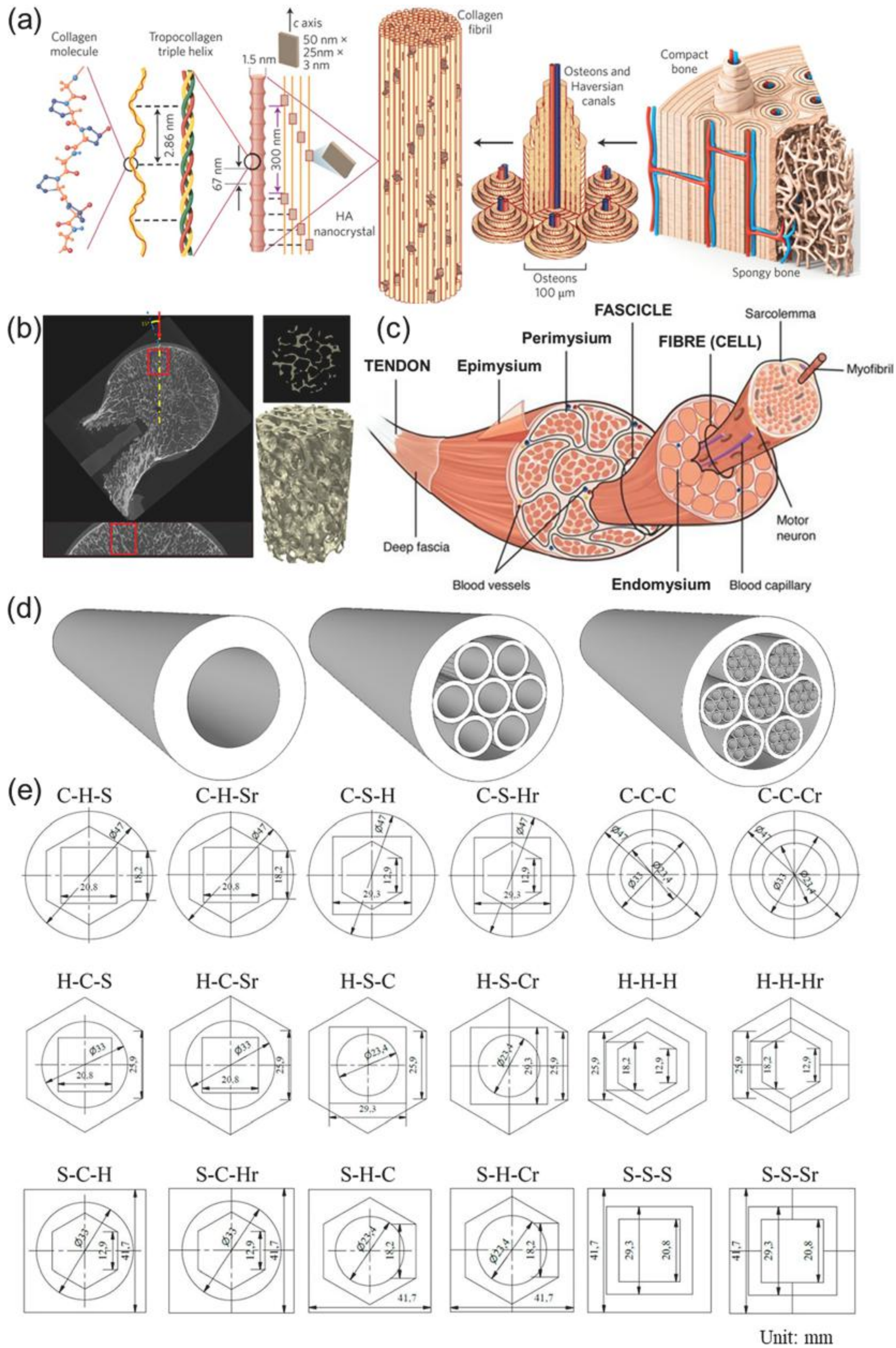

Fig. 8. (a) Hierarchical structure of bone at multiscale [51]; (b) Trabecular bone with 3D cellular structure [149]; (c) Schematic of the hierarchical structure of skeletal muscles [156]; (d) Tendon-inspired hierarchical tubular structure [157]; (e) Nested structures inspired by the Haversian system of the cortical bone and their different shapes (i.e., circle, hexagon and square geometries included) [158].

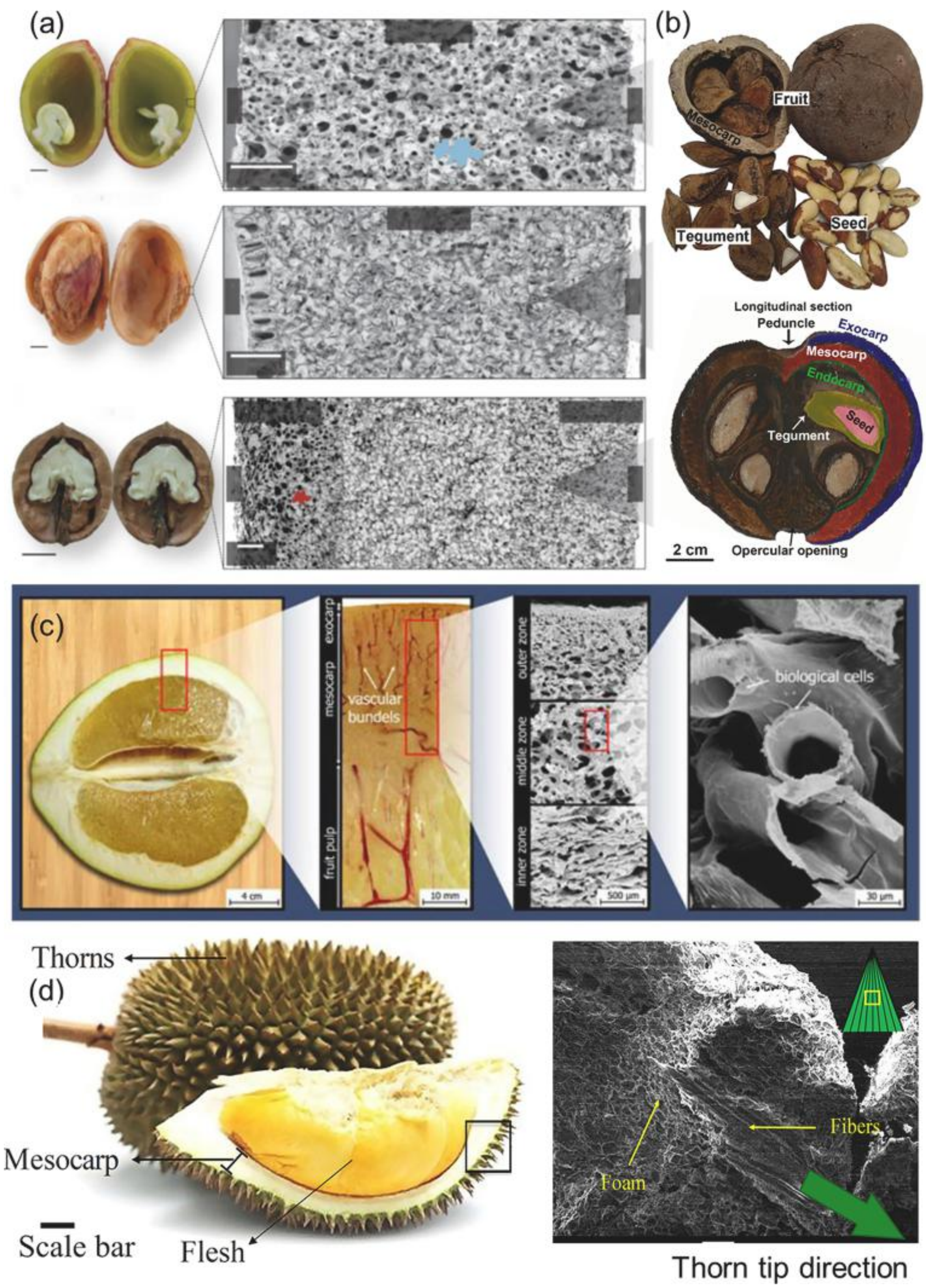

Fig. 9. (a) Characterization of pistachio (top), peanut (middle), and walnut (bottom) shells: optical images and microstructures [165]; (b) Seed, tegument, fruit, and longitudinal section of Brazil nut (Bertholletia excelsa) [166]; (c) Macroscopic and microscopic structure of pomelo peel [167]; (d) Tropical fruit durian (Durio zibethinus) and the microstructure of thorns [168].

neighboring ribs. By employing the beam-model, a continuum model was then developed to unveil the fundamental relationship between the continuum components (e.g., stress, strain) and geometric parameters.

2.5. Bone and muscle-inspired structures

Collagen, the most representative organic material with structural hierarchy, is the building block of biological tissues, such as bones, tendons, and muscles [129–148]. Over thousands of years of evolution, bones (containing inorganic minerals and organic phases) have been naturally optimized

structural configurations of high efficiency for supporting body weight, resisting external loadings, and absorbing impact energy [149]. Notably, hierarchical structures of bone (Fig. 8(a)) are designed with outstanding mechanical properties from the nanoscale to the macroscale, and play a vital role in physiological process (e.g., bearing weight and impact resistance) [150–152]. The trabecular bone (Fig. 8(b)), a 3D cellular structure with interconnected rod- and plate-like struts [149,153], is responsible for transferring loads by structural adaptation. According to the applied mechanical loadings, the bone can be structurally adapted through the microstructures, differentiating the mechanical properties of the corresponding regions (e.g.,

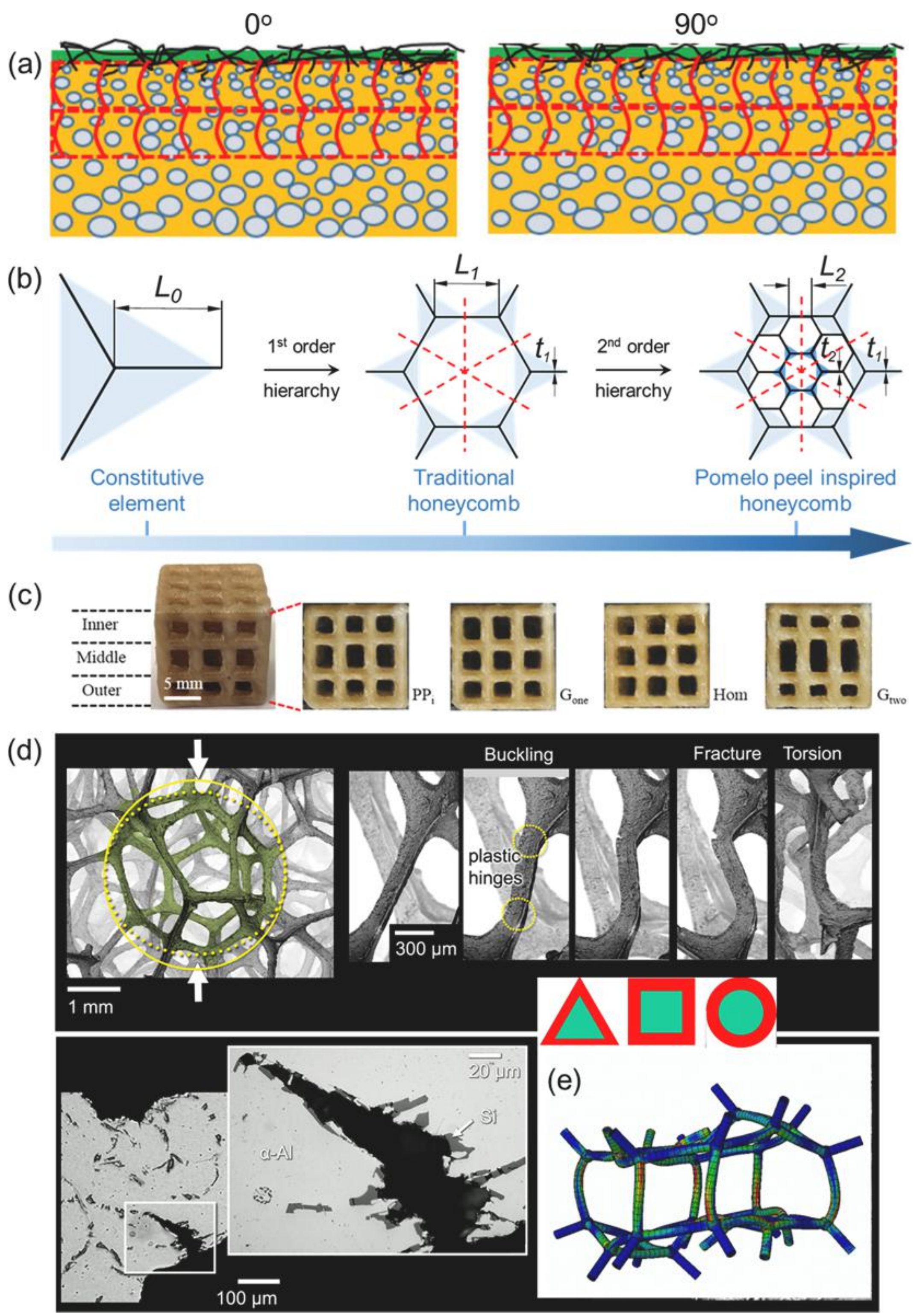

Fig. 10. (a) Bio-inspired composites with different angles of spacer [181]; (b) Pomelo peel-inspired hierarchical structure [182]; (c) 3D-printed structures inspired by pomelo peel [183]; (d) Microstructure and deformation of open-cell Al alloy foam [177]; (e) Numerical analysis of the structure under the loading, with the effect of the struts' cross-section considered, including triangular, square and circles [184].

tensile and compressive [154,155] ... exhibit a ... configuration (Fig. 8(c)). Connected to the tendon, Another inspiring example is the skeletal muscle (attached by dense and tough tissue, e.g., epimysium), as the fat bundle tendon connects the musculoskeletal system. The primary function of muscles is ... and the ... (e.g., perimysium). The ... of skeletal muscle executes the skeletal movement ... the muscle fibers ... endomysium. Meanwhile, playing a significant role to contribute ... the corresponding fiber, ... delicate organs [156]. The microstructure of cross-sectional ... a well-organized arrangement ...

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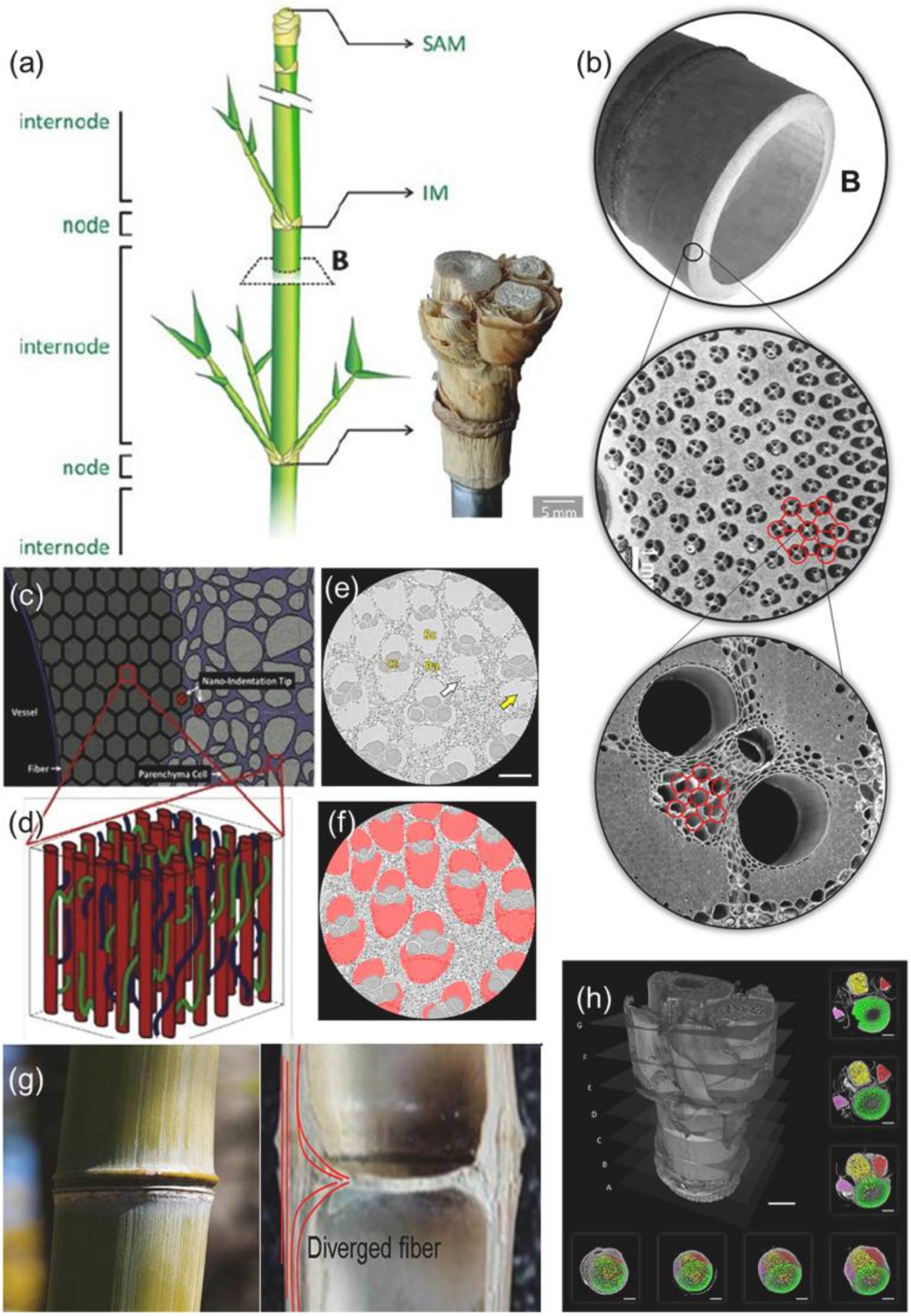


Fig. 11. (a) Macrostructural characteristics of bamboo; (b) Bamboo culm wall, micro-structure of bamboo cross-section, vascular bundles [46]; (c) Nanoindentation on the constituent materials of bamboo [187]; (d) Molecular structure of bamboo cell wall [187]; (e) Original μCT slice and (f) μCT slice with vascular bundles marked of a bamboo sample (B. edulis) [199]; (g) The structure of bamboo node included external ridge and internal diaphragm [201,202]; (h) μCT reconstruction of bamboo node showing the connected branches [196].

numerical analysis using the homogeneous and detailed FE models to evaluate the contribution of different structural features (e.g., materials, shape, patterning, thickness and design) to improving the properties of the bio-inspired materials (Fig. 10 (e)).

2.7. Bamboo-inspired structures

Bamboo is a lightweight and high-strength sustainable bio-composite material with a combination of remarkable mechanical properties (e.g., high strength, impact resistance and energy absorption behaviors) [188–190], making it one of the most attractive candidates for bio-inspired structures (Fig. 11) [191–195]. At the macroscale, bamboo stem contains hollow internodes and solid nodes (Fig. 11 (a)) [196]. Microscopically, bamboo culm (Fig. 11 (b)) has hierarchical structure mainly composed of cellular composites, i.e., fibers and parenchyma cells (Fig. 11 (c)) [197]. Given various environments (e.g., wind and snow), the gradient distribution of vascular bundles and nodes endow bamboo with an efficient load-bearing and impact-resistance capability.

Down to the molecular level, the major building blocks consist of cellulose microfibrils (Fig. 11 (d)), which are embedded in amorphous hemicellulose and lignin matrix [198]. Meanwhile, X-ray microtomography (μCT) further shows the thickened secondary wall and the functions of accommodating complex

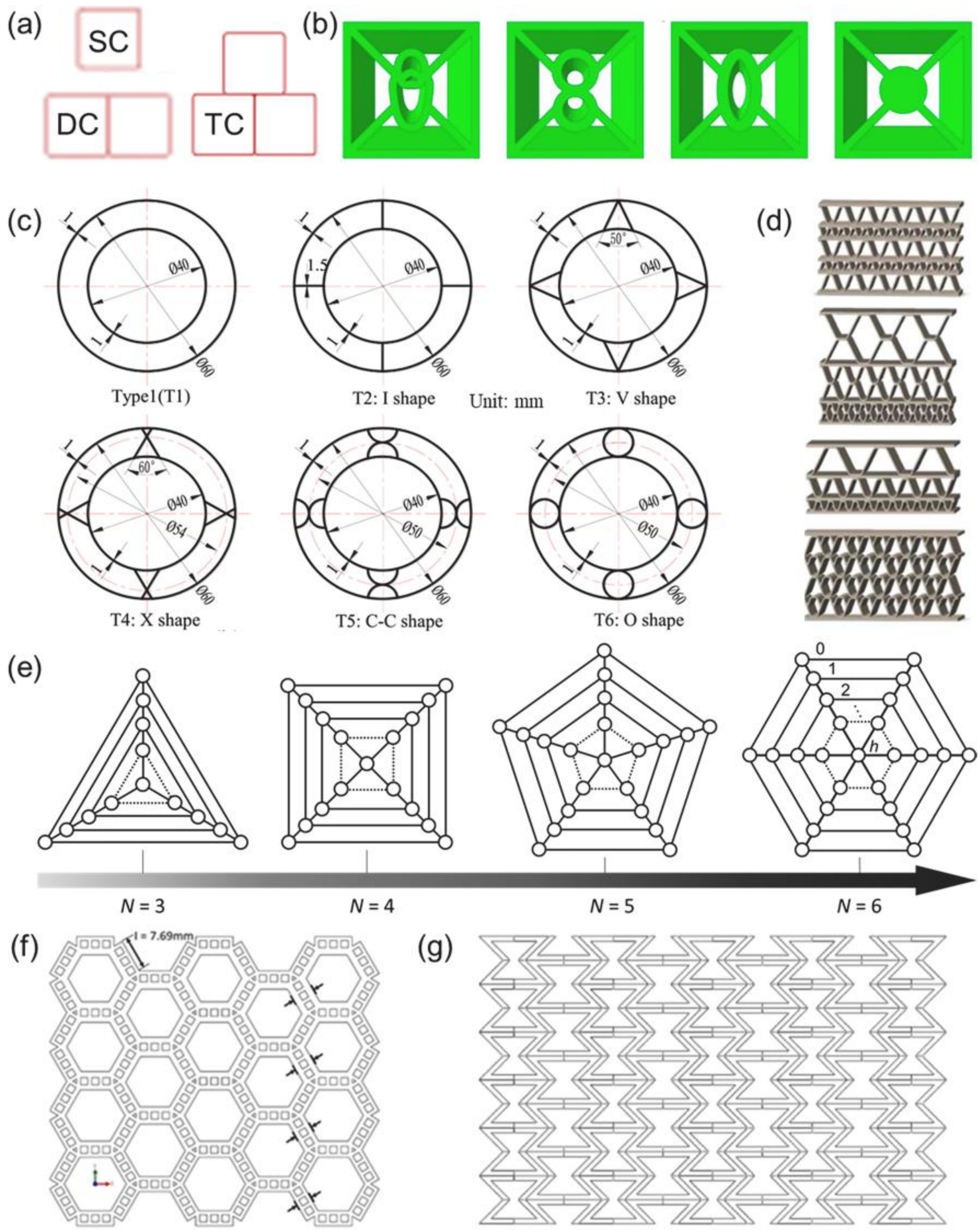


Fig. 12. (a) Bio-inspired multi-cell tubes [207]; (b) Cellular structures ... (c) ... [199]; (c) Bionic tubular structures from bamboo [208]; (d) Protective structures ... hierarchical structures [209]; (e) Bamboo-inspired ... honeycomb structure [215]; (f) Bamboo ... [216]; (g) Self-similar ... auxetic ... re-entrant ... honeycomb ... [211].

environment (Fig. 11(e)-(f)) [199] ... fiber bundle (Fig. 11(h)) [196]. A systematic experimental study ...

Despite the primary focus on the characterization ... the nodal region ... effect ... the bamboo ... contribution ... compressive ... of bamboo [200]. ... (Fig. 11 ... According to Huang et al. [203] ... (g)). Typically ... crushing ... bamboo material ... different ... parallel ... perpendicular to the fiber orientation ... bamboo ... material is ... dependent ... isotropic ... corresponding ... the increase ... dynamic ... mechanical ... bamboo material ... lamination ...

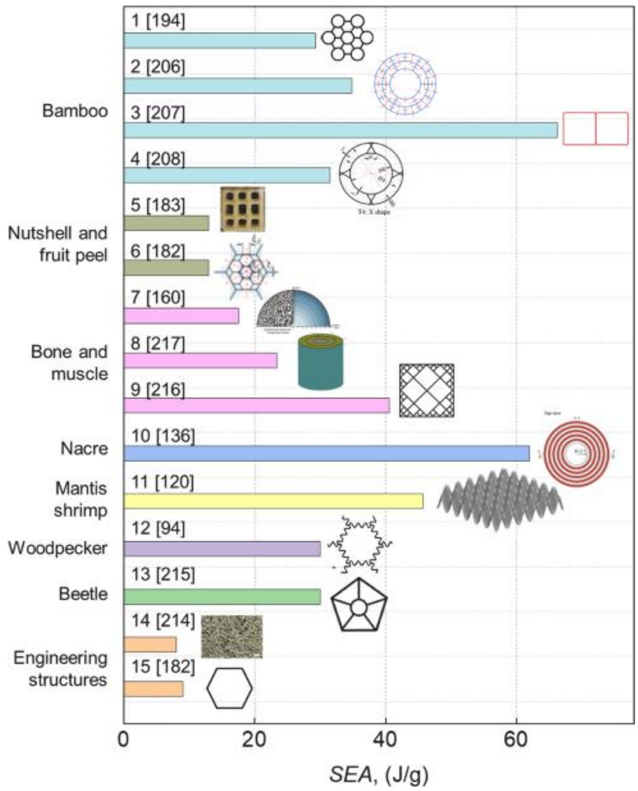


Fig. 13. Comparison of energy absorption capability between many widely-used engineering structures and representative bio-inspired structures [94,120,136,160,182,183,194,206–208,214–217].

of buckling/fracture mechanism, collapse mode and crack propagation. Based on the distinguishing characteristics of the bamboo culm, various bamboo-inspired designs and structures have emerged in recent years [191–206] (Fig. 12).

Inspired by the specific distribution of individual vascular bundles in the bamboo culm, Hu et al. [207] designed and fabricated a representative unit lattice-core tube made of CFRP and aluminum with a star-circular shell (Fig. 12(a)), where progressive buckling and stable progressive folding deformation modes were observed in the CFRP and aluminum tubes, respectively. Further experimental investigations revealed that the number of vascular bundles has a great effect on the crashworthiness. Subsequently, for design, the structure was further modified according to the gradient distribution of individual vascular bundles (Fig. 12(b)), achieving improvement in both strength and energy absorption performance [199].

Since the vascular bundles in the bamboo culm decrease from the outer layer to the inner layer, the reinforcement is arranged in a graded distribution. Furthermore, the functional region of bamboo, the nodes, also has the effect of enhancing the mechanical properties of structures [191,211,213]. Referring to the strengthening effect of nodes and diaphragms in bamboo materials, a bionic-bamboo structure was proposed by adding different rib configurations between two cylinders (Fig. 12(c)); the energy absorption performance was largely affected by the diaphragm parameters (i.e., number, thickness, and distance) [208].

Moreover, Palombini et al. [209] synthesized the findings on the bamboo microstructure (i.e., gradient distribution and hierarchical structure), and then transformed them into bamboo-inspired sandwich structures with corrugated cores for marine applications (Fig. 12(d)). The predominant failure mode was local buckling of nodes, and then the developed analytical model based on the buckling theory can fully predict the compressive failure and collapse sequence. More recently, Zhang et al. [55] conducted a comprehensive study on bamboo-inspired polygonal tubular energy-absorbing structures with multi-cell and hierarchical architecture, and elaborated the relationship between the topological factor, hierarchical level, and impact-resistance performance (Fig. 12(e)).

In addition, inspired by the strategies of thin-walled multi-cell tubes and gradient plates, introduced a bio-inspired microstructure with thickness self-repeat, essentially a functionally graded honeycomb, subjected to in-plane load (Figs. 12(f)), demonstrating higher energy absorption (a combination of buckling mechanism) than the traditional honeycomb [210]. According to the concept of "functional gradient" of bamboo composite, Jiang et al. [211] designed a bio-inspired auxetic honeycomb (Fig. 12(g)) and achieved enhanced crashworthiness and different advantages.

Table 1
Summary of materials and dimensions of bio-inspired structures in Fig. 13.

No.	Biological systems	Bio-inspired structures		
		Material	Cross-section (mm)	Height (mm)
1	Bamboo	Al 6061-T5 aluminum alloy	Overall 100 × 90	100
2		AA6061 aluminum alloy	Outer diameter 60	120
3		CFRP	120 × 60	100
4		6063-T5 aluminum alloy	Outer diameter 60	100
5	Nutshell and fruit peel	PEEK filament	16 × 16	16
6		AA6061-T4 aluminum alloy	Overall 84 × 97	20
7	Bone and muscle	Stainless steel tube with the aluminum foam filling material	Outer diameter 40	40
8		6063-T5 aluminum alloy and aluminum foams	Outer diameter 60	60
9		Al-6063-T5 aluminum alloy	100 × 100	240
10	Nacre	T300 CFRP Pre-preg carbon/epoxy	Outer diameter 28	50
11	Mantis shrimp	AlSi powder	Overall 42 × 42	12.4
12	Woodpecker	AA6060 aluminum alloy	Overall 54 × 54	17
13	Beetle	AA6061-O aluminum alloy	Overall 45 × 45	150

3. Insights and outlook

3.1. Bio-inspired structures for engineering applications

The target of bio-inspired design is to achieve superior structural performance for specific engineering demands and address bottlenecks. Nevertheless, most of the bio-inspired works are meaningless unless they show the potential and suitability for practical applications that significantly outperform existing engineering structures. Herein, we compared the energy absorption performance of impact-resistant structures used in engineering applications (e.g., honeycombs and aluminum alloy tubes/foams) and bio-inspired structures under axial load (Fig. 13). For a fair comparison, the energy absorption capability (i.e., SEA) with a unit of J/g is adopted to eliminate the effects of mass differences between these structures. Given the potential energy absorption performance of bio-inspired thin-walled tubes, the dimensions of cross-section, height and materials are summarized in Table 1.

Subjected to quasi-static axial compression, the SEA of conventional engineering structures is roughly 10 J/g. Nevertheless, the SEAs of bio-inspired structures are much higher and can even achieve more than 60 J/g (e.g., carbon-composite tubes [136] and bamboo-inspi

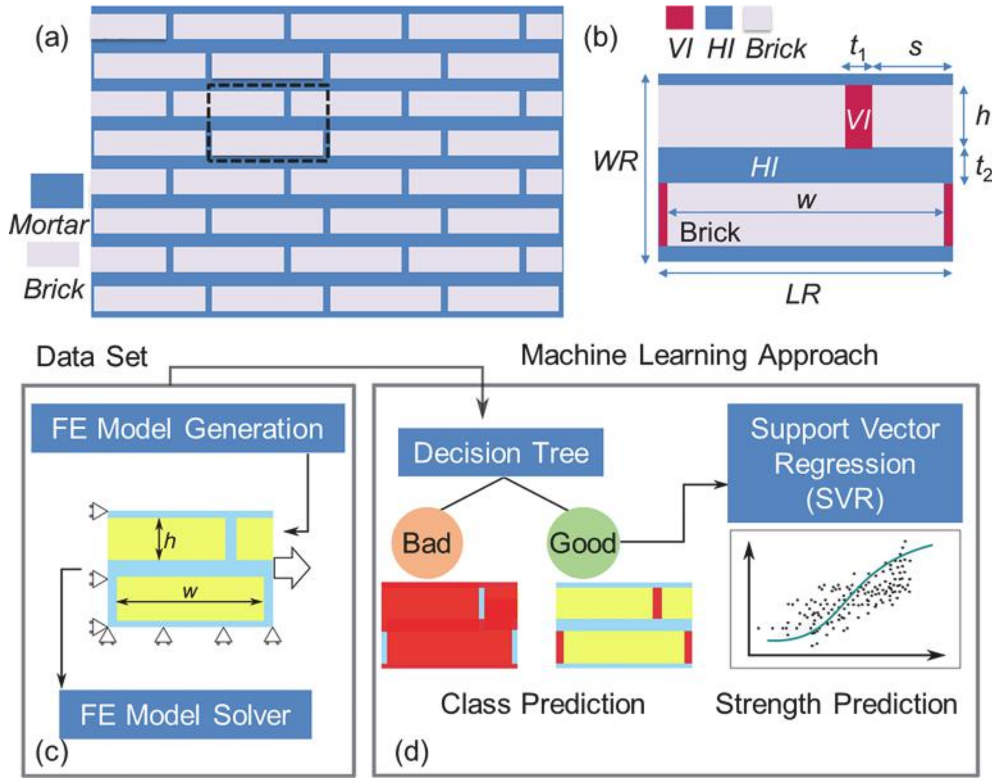


Fig. 14. Machine learning-based design of nacre-inspired composites: (a) brick-and-mortar structure; (b) the corresponding representative volume element used in machine learning; (c) data generation based on FE model; (d) machine learning model for classification and prediction [220].

multi-scale tubules [207], which may greatly enhance the energy absorption capacity in addition to the axial load bearing structural performance via ... For instance, the SEA of ... bio-inspired honeycomb ... about 2.5 times higher than those of traditional honeycomb with the same section [182]. In contrast to standard quasi-isotropic and cross-ply laminates, helicoidal laminates inspired by ... can minimize the internal damage, enhance damage tolerance, and improve the efficiency by suppressing ... under low-velocity impact [48]. It is also demonstrated that the bio-inspired helicoidal CFRP showed enhanced ductility, promising in applications of complex manufacturing of high-performance and damage-tolerant materials [218].

... under ... armor and protective structures. However, there may exist ... effects on non-uniformity ... structures ... greatly ... the mechanical performance of bio-inspired structures ... the fundamental ... manufacturing ... low-cost manufacturing for mass ... expensive ... bio-inspired engineering applications ... from nature.

With the rapid development of characterization techniques in recent decades (e.g., SEM, TEM, AFM, and µCT), the complex architectures of natural materials are accessible now; nevertheless, only touching the tip of the iceberg. An in-depth understanding of the structural-functional relationships is a prerequisite for appropriately transferring and integrating natural structures into ... (e.g., extracting basic design elements), therefore exploring the mysterious natural design principles.

Given the well-designed structures of biological systems, manufacturing is an important ... to demonstrate ... application. Various advanced technologies (e.g., additive manufacturing) make it possible to fabricate bio-inspired energy-absorbing structures using different materials (e.g., plastics, metals, ceramics, and composites). For example, extrusion-based 3D concrete printing has been applied to manufacture bio-inspired Bouligand structures with different pitch angles (0°, 15°, 30°, and 45°), where ... showed that the helicoidal ... outperformed ... [219]. Thus, bio-inspired structures are promising competitive candidates for future impact-resistant applications ...

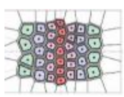
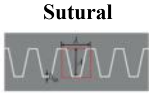
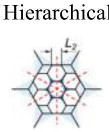
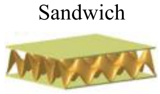
3.2. Bio-inspired structures and machine learning

Machine learning (ML) is recognized as a highly effective tool to address ... complex relationships between specific factors, which is tailor-made for the structure-function relationships in the bio-inspired structures. Despite its immense potential, the implementation of ML in various engineering fields is comparatively limited in ML-based research on bio-inspired designs.

Remarkably, by extracting critical features from various mechanical parameters, ML shows a high capacity in processing large data ... towards optimal bio-inspired structures with high performance. Mora-... et al. [220] applied ML-assisted ... design strengthened nacre-like brick-and-mortar composites ... ceramic matrix (Fig. 14(a)). Based on a representative volume element (Fig. 14(b)), the critical geometrical parameters (i.e., brick aspect ratio ...) were obtained as ... generated from FE simulations. Following that, the ML model was trained to uncover the relationships ... with the mechanical properties of the bio-inspired structures. Accordingly, the classification (“good” or “bad” designs) and prediction of the target mechanical properties can be achieved (Fig. 14(c)).

Although ML-assisted approaches are featured by the computational efficiency ... accuracy ... the main challenges ... focus on ... homogenization ... features,

Table 2
Summary of critical characteristics of structural elements for ML applications.

Structural element	Representative systems	Scale	Critical features
Tubular 	Beetle, bamboo, keratin-based hooves, human teeth, horns	Micro	Diameter-to-thickness and height-to-thickness ratios, volume fraction, pore shape (e.g. circular, elliptical, square), orientation
Bouligand 	Mantis shrimp, sponge, [illegible] exoskeletons, arthropods	Nano, Micro, Macro	Fiber orientation angle (i.e., the pitch angle), overall length between the neighboring fibers, total number of layers, stacking sequence
Gradient 	Pomelo peel, conch, bamboo, tooth, dentin, horse hooves, yak horn	Micro, Macro	Gradient direction, gradient type (e.g., continuous gradient, stepwise gradient), stiffness/density/size/shape/porosity gradient
Cellular 	Bee, Woodpecker skull, coral, trabecular bone, porcupine quills	Nano, Micro, Macro	Cell type (i.e., open cell and closed cell with closed chambers), porosity, relative density, wall thickness, Poisson's ratio
Layered 	Nacre, fish scale, ligament, cartilage, conch, insect exoskeletons	Micro	The lamellar arrangement, interface geometry, out-of-plane thickness of each layer, and friction properties of the interface
Fibrous 	Collagen fiber (bone, tendons, muscle), spider silk, silkworm, wood	Nano, Micro	Fiber orientation, adhesion between fibers, fiber length, wave/kink of individual fibers, and the interweave of fibers
Sutural 	Turtle shell, woodpecker beak, mammalian skull, boxfish junctions	Micro	Suture geometry (sinusoidal/triangular/trapezoidal type), waviness, height-to-width ratio, hierarchical structure, tooth angle, interface thickness
Overlapping 	Seahorse, chiton, [illegible] shark skin, alligator, millipede exoskeleton	Macro	Projecting length of individual plates, spacing between plates, curvature radius of overall structure, angle between distal ends of two adjacent plates, curved status
Hierarchical 	Almost all biological systems with hierarchical self-assembly from nano to macro scale	Nano, Micro, Macro	Hierarchical critical features, building blocks (e.g., cellular, tubular elements) that form the structure (e.g., size, shape)
Sandwich 	Coconut, [illegible], pomelo peel, bamboo stems, toucan beak, bird bones and feathers	Micro, Macro	The thickness of the shell and porous structural core, with geometries (e.g., size, shape, and relative density)

simplified design and manufacturing, [illegible] mechanical properties. There are various bio-inspired approaches [illegible] ML-assisted structural design [illegible] summarized in Table 2. Also, more detailed [illegible] ML design strategies need further exploration of the design space.

4. Conclusions

Despite [illegible] natural materials always serve as [illegible] and continuous [illegible] fascinating [illegible] bio-inspired structures [illegible] mechanical performances, such as ultra-high specific strength, toughness, energy absorption, and impact resistance. Based on seven [illegible] elements [illegible] bio-inspired structures [illegible]. The biomimetic structures demonstrate enhanced performances such as energy absorption capacity. Finally, we summarized the critical features of structural elements [illegible] bio-inspired structures. We also note that [illegible] bio-inspired engineering applications [illegible] fundamental challenges [illegible] more sustainable [illegible] efficient [illegible] manufacturing technologies.

CRediT authorship contribution statement

Wen Zhang: Writing – original draft, Methodology, Investigation. Jun Xu: Supervision, Writing – review & editing. [illegible]: Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported partially by the funds provided by the University of North Carolina at Charlotte.

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