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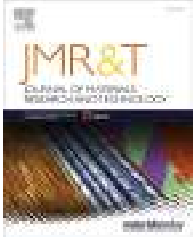

Review Article

An insight from nature: honeycomb pattern in advanced structural design for impact energy absorption

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ABSTRACT

The ability of a vehicle to protect its occupants from serious injuries in the event of a collision is defined as crashworthiness. The proper design of lightweight energy absorption components is a topic of interest because it can enhance the occupant's safety and lead to less fuel consumption and gas emission. Honeycomb structures are known to have excellent mechanical performances, which are mainly due to the configurations of the unit cell. Thus, they have attracted attention in the field of automobiles, railway vehicles, etc. In the present work, the criteria of crashworthiness as well as the nature-bioinspired cellular structures are first introduced. Then, the various classifications of advanced honeycomb design, including graded, hierarchical, and sandwich panel-based honeycomb structures, are established and discussed with a focus on the advantageous effect of various designs on the crashworthiness of honeycomb-based structures. Finally, the importance of potential design to enhance the crashworthy performance of honeycomb structures together with the future challenges is summarized. This work provides a good understanding of architectural design for a new generation of advanced honeycomb-based structures with efficient energy-absorbing properties.

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1. Introduction

Nature can provide solutions for the current automotive industry, public healthcare, and technologies such as sensor and energy systems. The impact during an accident can cause occupant injury and even death in severe cases. A collision during transportation largely contributes to global injury and death. Additionally, the annual economic burden related to the impact collision is estimated to be 7.2 billion USD in 2018 [1]. Given the massive social and economic effects, the demand for lightweight structures possessing high energy-absorbing capability is increasing in various engineering fields, comprising the automobile, aerospace, energy storage, sensor, etc., [2–4]. Given the design concept, nature has provided us with novel structures with high-impact tolerance capabilities [5,6]. This led to the introduction of bioinspiration, which is known as the integration of scientific fields including biology and materials science. The bioinspired design typically mimics the natural structures using modern manufacturing techniques to obtain comparable functionality [7]. For example, wood and bones with lattice structures often show remarkable mechanical properties and are known as natural energy absorbers [8]. Furthermore, the peel of pomelo fruit provides significant impact protection when falling on the ground [9]. Thus, nature can be an inspiration to develop and design man-made structures with high energy absorption [10].

Public healthcare has been progressively utilizing various types of sensors to reduce the burden on the medical organization and the total costs [11]. Nonetheless, their rigidity, low sensitivity, and sensing range significantly limit their practical applications in eco-friendly and real-time accurate monitoring. Hung et al. [12] fabricated a dual type of sensor using MXene/cellulose nanofibers and their findings showed that the sensor possesses excellent stability and degradability. Additionally, small external stimulus and huge pressure load were both sensed by the sensor which indicates its high sensitivity. In another study, Shan et al. [13] introduced ferric ions into the poly (N- [tris (hydroxymethyl) methyl] acrylamide-co-acrylamide) (P (THAM/AM) hydrogel crosslinked with cellulose nanofiber. The hydrogel strain sensor was found to be highly sensitive with superior durability by which both large and small motions were translated into the relative resistive changes when attaching to the human skin.

The production of energy from renewable energy sources as an alternative to fossil fuel is growing and this further increases the need for efficient energy storage systems such as batteries [14]. In this framework, gel polymer electrolytes (GPE) as nature-sourced constituents can be considered valuable alternatives in the large-scale manufacturing of cells. In this regard, cardanol-derived epoxy resin [15] and lignin [16] were used to produce biobased GPE in potassium-ion batteries and the results showed excellent electrochemical stability and proper ion conductivity in the potassium-ion battery. Also, dextran-based nanosponge [17] and carbonized hyper cross-linked cyclodextrins-based nanosponge [18] have been used as organic filler in the liquid electrolyte for lithium-ion battery and high-capacity electrodes for lithiated Si–S batteries, respectively. The findings showed that nanosponge could significantly enhance the safety and cyclability of the cell by the stabilization of the metallic lithium interface [17] and lead to stable cycling performance by limiting the dissolution of polysulfide on the sulfur cathode [18].

The cellular structures have the potential to absorb severe energy. The optimal design of cellular structures is a key parameter that can influence the load transfer and lower the damage severity [19]. The honeycomb bee is another type of natural structure, which possesses a cellular structure with a periodic topology. Different configurations have been developed, including hexagonal, triangular, circular and square, by inspiration from honeycomb [20]. Additionally, the honeycomb core has been the topic of interest among researchers and industries to produce sandwich structures for certain applications such as crashworthiness [21]. The rationale behind this is due to their extraordinary properties such as negative Poisson's ratio (NPR), negative stiffness, etc [22]. As it can be observed from Fig. 1, the investigation of the honeycomb-based structures for energy-absorbing has been started since 2000 and the number of publications is rapidly increasing. Thus, they have been widely used in the field of railway vehicles, automotive and aerospace [23,24].

Some prominent reviews have been published on bioinspired structures with a focus on additive manufacturing of bioinspired structures such as “Bioinspired energy absorption material designs using additive manufacturing” [25], “A review of recent research on bio-inspired structures and materials for energy-absorbing applications” [26] and “A review of impact-resistant biological and bioinspired materials and structures” [27]. Moreover, reports have shown the great potential of honeycomb structures for impact-absorbing applications [28,29]. Although previous reviews focused on the description of unique characteristics and remarkable mechanical properties of biological structures including plants and animals and showed their potential to be mimicked for designing efficient energy absorbers, nonetheless the specific design of crash-absorbent structures inspired by honeycomb is not fully covered. Therefore, the objective of this review paper is to comprehensively investigate the latest developments in the bioinspired design of advanced honeycomb-based structures for impact tolerance applications. Therefore, studies are mainly focused on material properties, geometric parameters and the presence or absence of defects in the structural behavior aiming at achieving higher energy absorption capacity [30–35].

2. Search strategy

Database PubMed was used for the bibliographic search. The electronic search was done by gathering the previously published papers from January 2011 until December 2021 to look for related papers on the crashworthiness of honeycomb-based structures. The authors used the terms “Honeycomb” AND Crashworthiness”, “Bioinspired” AND “Energy absorption” or a combination of thereof in the search. The following criteria were considered for this review paper: (1) English written papers; (2) original research articles and review papers; (3) energy absorption; (4) buckling deformation. A total number of 430 articles were retrieved. After the elimination of

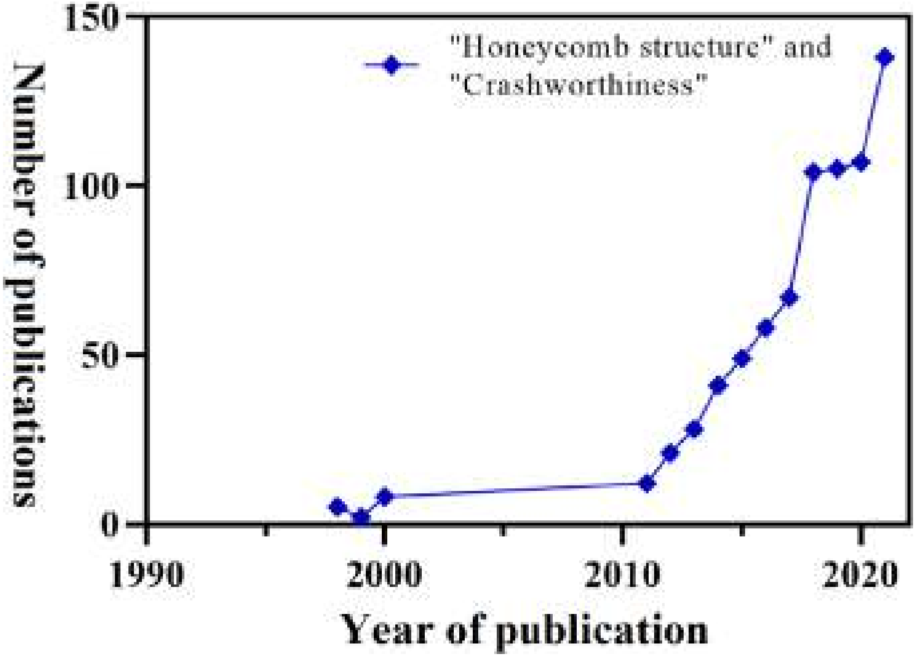

Fig. 1 – The number of publications of honeycomb-based structures for crashworthiness applications, based on the PubMed database (https://pubmed.ncbi.nlm.nih.gov/) a web-based information service.

duplicate references, 161 articles were selected for this review paper.

3. Crashworthiness criteria

The performance of energy absorption is a key mechanical characteristic in energy-absorbing structures. The energy absorption process converts the input kinetic energy during collision into strain energy by plasticity, friction as well as viscoelasticity. Thus, the kinetic energy, which is released during the impact of a moving vehicle, is converted into plastic deformation energy through an installed energy-absorbing device. The material properties, deformation modes, loading conditions as well as structural configuration significantly affect the performance of energy absorption in a structure [36]. The dampers and energy absorbers are useful constituents that are used for energy absorption applications in modern industry [25]. The energy is absorbed via plastic work in mechanical dampers. Among commonly used dampers, cylindrical shells are capable of damping energy via plastic deformation under axial loading. Crashworthiness is defined as the vehicle capability to protect passengers from serious damage during an impact collision [37,38]. The initial purpose of conducting the crashworthiness in several frames such as vehicles, helicopters, etc. Is to protect people during unfortunate occurrences including crashes and collisions. In this regard, the performance of energy-absorbing structures is measured by the parameters comprising energy absorption capacity (EA), specific energy absorption (SEA), mean crushing force (MCF), crush force efficiency (CFE) and energy absorption efficiency (EAE). These parameters are obtained from the force-displacement curve under crushing load. The SEA and EA parameters have been used as key indicators to measure the crashworthiness of composite structures (Table 1).

Three steps are involved in the axial crush process. In the first step, the crushing load is reached a maximum value. Then, the initial resistance of the cylindrical sample is overcome. Thereafter, the load is reduced and fluctuated simultaneously; the crush and deformation are started and continued. A dramatic increase in the force is observed in the final stage; the increase in deformation is also observed until reaching a final amount. This slight difference in this final stage may be due to the structure of the damper [34]. The parameters that should be measured for the evaluation of a damper sample are initial peak force (P_{peak}), average force (P_m), energy-absorbing capacity (E_a) and the shape factor (h). Also, the limiting factor in design is the weight.

Table 1 – Formulas and the corresponding definition of crashworthiness indicators [26].

Parameter	Equation
EA	$\int_0^{d_c} F(x)dx$
SEA	$\frac{EA}{m_c}$
MCF	$\frac{1}{d_c}\int_0^{d_c} F(x)dx$
CFE	$\frac{MCF}{F_p}$
EAE	$\frac{1}{\sigma_s}\int_0^{\varepsilon_c} \sigma(\varepsilon)d\varepsilon$

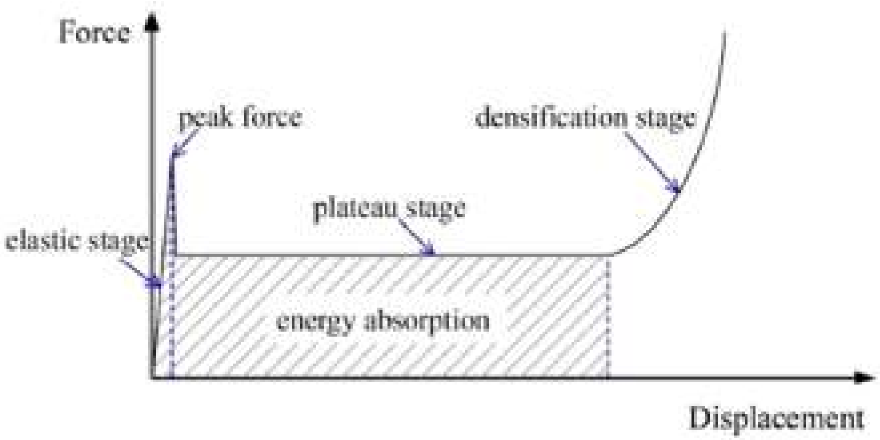

Fig. 2 – Schematic representation of force-displacement curve in an energy-absorbing structure under dynamic compression. Reprinted with permission [40].

The SEA is the energy absorption of the crushed mass (m_c), which is frequently used for the comparison of the energy-absorbing capabilities of various structures. The energy absorber is expected to have a long stroke and experience more plastic deformation along the loading direction. This leads to achieving a high SEA. The crushing energy dissipation through plastic deformation of an energy-absorbing structure is mainly evaluated by EA, which is defined as the integration of crushing force F(x) to displacement over the crushed structure distance (d_c). The MCF is defined as the division of total absorbed energy by the crushed structure distance. In addition, the ratio of the mean crushing force to the peak crushing force (F_p) is the definition of CFE. Finally, the division of total stress $\sigma(\varepsilon)$ by the stress (σ_s) at the strain (ε_s) is EAE. Increasing SEA, EA and CFE and decreasing initial peak force during collision indicate that the energy absorber can be potentially used for crashworthiness applications. Nevertheless, increasing the initial peak force lowers the overall performance of crashworthiness. The EA is commonly analysed by the displacement versus load plot under impact loading. The diagram of a typical force-displacement curve in an energy-absorbing material under dynamic compression is schematically illustrated in Fig. 2 [40].

Four stages can be found in the curve: elastic, region in between peak and plateau, plateau and irreversible. In the elastic region, the material deformation is elastic and reversible, while in the plateau stage the reactive force is kept constant due to the irreversible plastic deformation. The shaded area, which is enclosed under the curve, indicates the total energy absorption. Djamaluddin et al. [41] have optimized the foam-filled tubes under axial and transverse impact loading. They have achieved the suitable peak and the mean force with maximum energy absorption through the evaluation of failure in three distinct energy-absorbing structures. An energy-absorbing structure such as a crash box is the key subject in any kind of crashworthiness study [42]. The installed crash box in a vehicle is a thin-walled structure that is made up of metal or composite materials. It is mounted on at frontal area of the vehicle and is employed as an energy-absorbing constituent to the vehicle because of collision during crashes [43]. This crash box is expected to have the capability to absorb the kinetic energy in a frontal crash, maintain the deceleration of the vehicle in a safe range and minimize the chances of injury to the occupants during collision [44]. Since most vehicle manufacturers are inclined to produce lightweight and safe vehicles, many lightweight materials have been studied as an alternative to metals to comprehend the reliability of these materials as the energy-absorbing constituent in the vehicle [45].

4. Experimental testing

The impact resistance of nature-bioinspired structures can be measured by simple compression, flexural and tensile tests utilizing the universal testing machine. Although the strain rate in these tests is limited to an impact regime of around 1-2 S^{-1}, however, it can still provide insight into deformation mechanisms. The loading conditions, orientations as well as strain rates make these testing methodologies different from each other. For instance, in quasi-static deformation, the sample is in static equilibrium. In contrast, the propagation of elastic and plastic waves is observed in dynamic deformations. Drop-weight testing is one of the most famous techniques which can reproduce impacts with a velocity below 25 m/s in the natural regime. These testing methods can provide a better understanding of impact resistance and the energy absorption of materials and is useful for the comparison of various materials under comparable circumstances. Low velocity (below 2 m/s), high velocity (0.5–1.5 km/

Table 2 – Impact testing methods and their corresponding strain rate.

Impact type	Method	Strain rate (s^{-1})
Low velocity	Drop weight	10^2
	Charpy/Izod pendulum	
High velocity	Hopkinson bar Taylor anvil	10^4
Quasi-static	Conventional testing machine	10^{-4}
	Servo-hydraulic	10^{-2}
		10°

Table 3 – A summary of impact resistant design and their mechanism of energy absorption.

Material property	Mechanism	Reference
Hierarchical	The synergetic performance of each layer enhances the overall impact of energy absorption	[48–50]
Gradient	Crack deflection, the collapse of the pore, fracture energy	[51–53]
Tubular	Buckling, collapse, delamination, crack deflection	[54,55]
Sandwich	Wrinkling of top face sheet, buckling of core, densification, shearing	[56–59]

s), and hypervelocity (2–3 km/s) are different types of impact [46]. The low and high-velocity impacts are usually applied to evaluate the energy-absorbing properties of structural materials. In low-velocity impact, there is sufficient duration for the contact between the impactor and the target and in turn, the structural material to respond and the overall deformation of the structure is coupled with local penetration. In contrast, there is not sufficient time for the structure to respond under high-velocity impact and localized deformations occur due to the propagation of stress waves through the structure. A summary of impact testing methodologies with their corresponding strain rates is summarized in Table 2.

5. Natural impact-resistant structures

Since the term biomimetic was introduced by Otto Schmitt in the 1950s [47], scientists and engineers have made effort to learn from biological structures. There are many structures of animals in nature offering excellent structures with high energy-absorbing capacity that can be inspired to design and fabricate novel structures with significant energy absorption. The impact resistance materials that can be found in nature possess porous, hierarchical, gradient, tubular and sandwich characteristics. The arrangement and magnitude of the above-mentioned characteristics. The hierarchical characteristic is defined as the distinct structural constituents in different length scales. The overall mechanical properties of the structure are improved by the synergistic performance of these elements. The self-assembly from the atomistic to macro-scale renders the hierarchical characteristics of natural structures. In hierarchical structures, the combination of small molecules into the larger constituents via bottom-top development results in the formation of a functional macro-scale constituent. The porous structure with different shapes and densities can be found in nature. The porous structure can enhance energy absorption while decreasing the overall weight. The gradient characteristic is defined as the changes in the architecture (for example porosity) and the properties (for example density) of a material. The tubular structure is made up of hollow channels, which are aligned along a particular axis. Finally, the sandwich structure is formed by two strong layers (face sheet) and one softer porous layer, providing a lightweight and strong energy-absorbing structure. The mechanism of impact energy absorption by each design element can be found in Table 3.

6. Nature-inspired cellular structure

Bioinspired design is defined as the incorporation of some of the functions and characteristics of biological organisms into novel structures. Currently, the development of new biomimetic materials with excellent energy-absorbing properties is desired [25]. The cellular structures can be potentially utilized as lightweight constituents due to their porous characteristic [60]. Porous materials are lightweight materials that enhance energy absorption [27]. The porous structure plays a key role in determining the impact resistance of the material. The arrangement and distribution of the porous

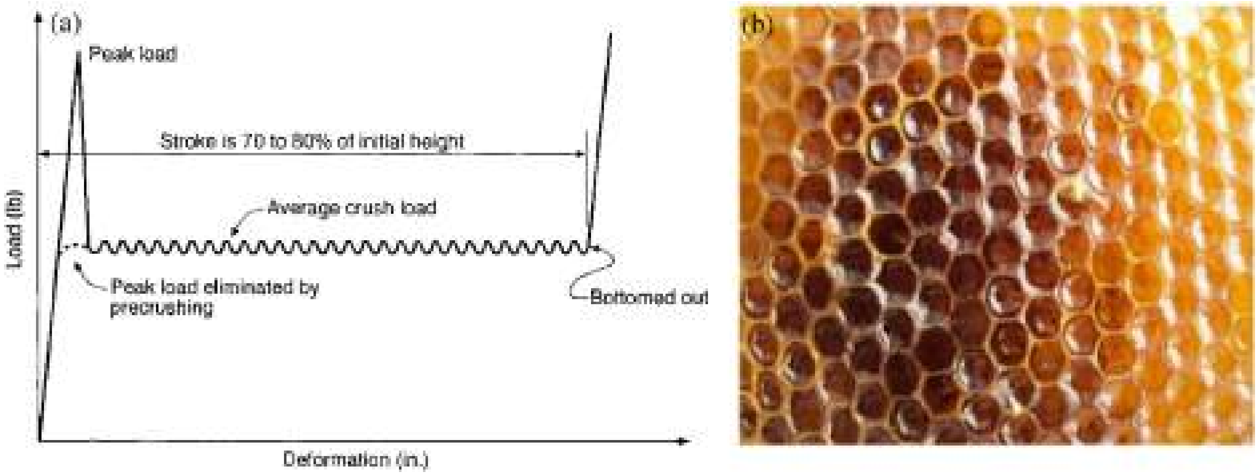

Fig. 3 – Honeycomb structure: (a) typical force-displacement curve for a regular honeycomb structure, (b) natural beehive. Reprinted with permission [69,70].

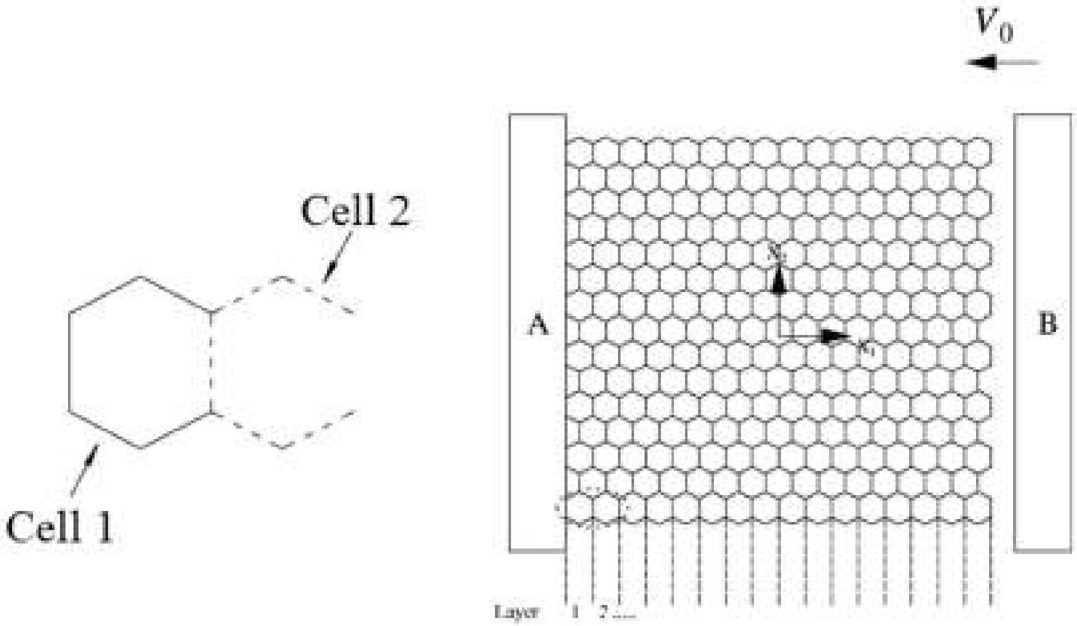

Fig. 4 – A schematic representation of graded honeycomb structure and cell structure. Reprinted with permission [79].

characteristics significantly affect the reaction of materials to dynamic stress. The biomimetic porous structures are naturally two-dimensional (2D) or three-dimensional (3D), such as honeycombs and tubes. Honeycomb is one of the biomimetic absorbers, which is called a nature-inspired energy-absorbing structure, which is discussed in the following section.

6.1. *Honeycomb*

The first artificial honeycomb was fabricated up of paper in China 2000 years ago. Then, the modern honeycomb products were manufactured probably in the late 1930s and the first aluminium sandwich panel was manufactured in 1945. Honeycomb is a porous material that possesses a high stiffness-to-weight and strength-to-weight ratio [61]. The commercial honeycomb unit cells are characterized by edge width, edge length, foil thickness and inclined angle, respectively. The pattern of the honeycomb structure is repeated unit cells that are extended in 2D unlike the other counterparts such as foams [62]. These repeated cellular arrays possess inherent adaptability and full surface compression is allowed due to their geometry [63].

The honeycomb structure is a thin-walled hollow shell with periodic cells (Fig. 3), that is developed through a cluster of hollow cells based on the ASTM C297-94 [59]. It is one of the prominent natural structures for bioinspiration to design thin-walled structures [65]. The lightweight honeycomb structure can be made from different materials such as aluminium, carbon, steel and fiberglass. From crashworthiness aspects, the honeycomb structure is particularly a good choice as an energy absorber [66] and is cost-effective. Thus, they have attracted attention for the applications such as a vehicle, automobiles, railways, etc. In a honeycomb structure, the energy-absorbing capacity of individual cells is inclined to be improved compared to those with singular extrusions. This is attributed to the interactions between the adjacent cells [67]. The crushing behavior of different honeycomb arrays under large deformation has been thoroughly reviewed by Thomas and Tiwari [68].

The mechanical behavior of honeycomb structures has been investigated in the past last decades including compression [71], buckling [72] and fatigue [73] tests, depending on the load-displacement, position and velocity. Therefore, they can be classified as elastic/plastic responses, static/quasi-static and dynamic responses, out-plane and in-plane responses, axial and oblique responses. The static/quasi-static and dynamic responses can be low, medium, high and hyper-velocity based on the speed of applied loading. In addition, the honeycomb structure shows the different mechanisms of energy absorption under different loading directions. The energy in honeycomb structure is mainly absorbed through the bending deformation of cell walls and plastic hinges at the cell wall joints under in-plane loading, while the energy is absorbed through buckling of cell walls and membrane deformations under out-plane loading [74] (Fig. 3). Thus, a high level of energy absorption is usually observed in the honeycomb structures under the out-plane direction. The nature-inspired honeycombs show a higher SEA compared to most metallic foam such as Cymat and Al-Poras foam at similar plateau stress [26]. Apart from the hexagonal honeycomb structure imitated by natural beehives, the triangular, square and circular honeycomb structures have also been proposed based on different polygonal variables. For example, Papka et al. [75] demonstrated that the size of the specimen has not significantly affected the energy absorption of a polycaprolactone circular honeycomb. Additionally, energy absorption capability was accurately predicted for different biaxiality. Conventional honeycomb structures have been extensively used as energy absorbers because of their low cost, simple structural configuration as

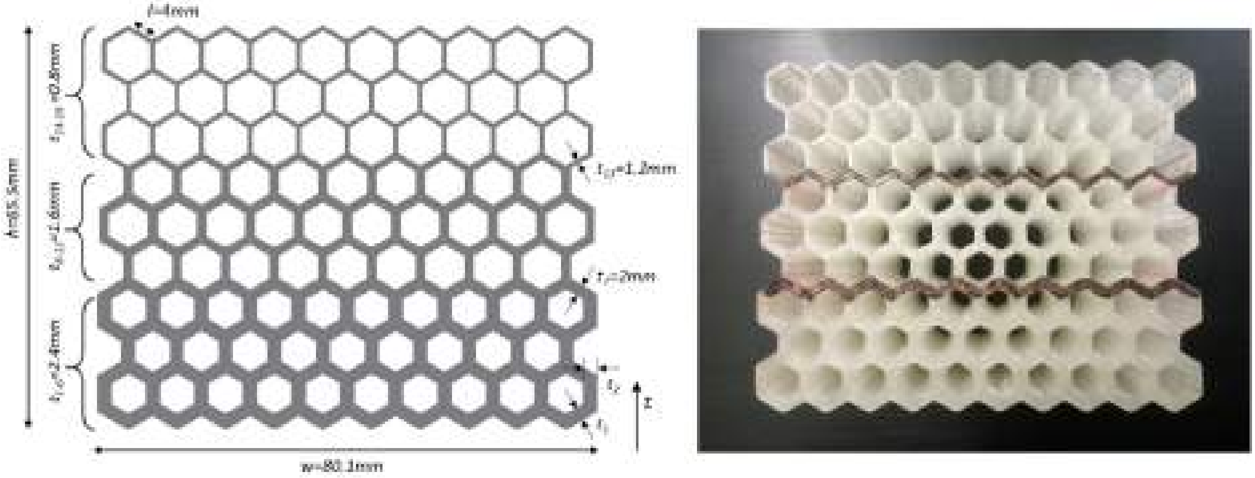

Fig. 5 – A sample of cell wall thickness-graded honeycomb structure with various thicknesses. Reprinted with permission [80].

well as ease of processing. Nonetheless, they showed poor energy absorption characteristics. Thus, researchers have made efforts to enhance the crashworthiness of the systems, particularly in terms of force efficiency.

7. Different types of honeycomb structures

7.1. *Graded honeycomb structures*

The gradients can be introduced into the wall thickness and cell width to manufacture the graded honeycomb structures. This stems from the anisotropic characteristics of honeycomb, which shows different properties in various directions. In the honeycomb with a graded configuration, the geometry is varied across the whole unit cells, unlike the honeycomb with a typical configuration [76]. The introduction of a gradient into the structure of a material can significantly reduce the weight and simultaneously enhance the performance using a reasonable design of gradient parameters [77]. The graded properties could be stemmed from geometrical parameters such as diameter, width and wall thickness. Also, they can arise from material parameters such as density, strength and type of material. Generally, the introduction of gradients provides bigger flexibility and a wider domain of design for the crashworthy performance of materials [67]. The graded honeycomb as a cellular material has been widely studied in energy-absorbing applications [78,79]. A typical graded hexagonal honeycomb is shown in Fig. 4. In this honeycomb structure, there are five edges with comparable values of yield stress and one cell on the right side with a different value. The material properties of these two adjacent cell walls bring graded characteristics aiding to have flexible control of the in-plane crushing collapse [79].

The sub-honeycomb structure with different characteristics could be constructed by the concept of the gradient in which a graded honeycomb is formed by the assembly of sub-honeycombs. Grading in the honeycomb could be induced by cell thickness [80–82], configuration parameter [83], cell configuration [84], material property [85], and hierarchical [28] structure, which yields different types of graded honeycomb structures. A typical structure of a thickness-graded honeycomb is depicted in Fig. 5.

The thickness of the cell wall, cell configuration, cell parameters and hierarchical filling control the grading properties of each sub-honeycomb. For example, Bates et al. [80] have studied the energy absorption of the graded hexagonal honeycomb structure and have shown great impact protection by cell wall thickness graded hexagonal honeycomb. In addition, Wu et al. [85] have investigated the energy-absorbing capacity of graded circular honeycomb structures. It was found that the matrix density gradient can control the energy absorption and dynamic response under in-plane loading. Ali et al. [81] have also shown the superior energy-absorbing capability of graded honeycomb over regular honeycomb structure. Zhang et al. [82] have shown a higher energy-absorbing capability and reduced tress peak for gradient hexagonal honeycomb structure with proper selection cell wall thickness gradient. Nian et al. [28] have studied the energy-absorbing capability of graded hexagonal honeycomb and demonstrated a better energy absorption for hierarchical filling graded hexagonal honeycomb than the uniform hexagonal honeycomb. The cell-angle gradient re-entrant honeycomb structure was also investigated. Wu et al. [83] have found that the energy-absorbing capability is improved by graded design under low velocity or quasi-static impact. Nonetheless, the enhanced energy absorption under high-speed impact could only be observed when the crushing direction is along the structural weak-to-strong direction. In another study, Hou et al. [86] manufactured the angle-gradient re-entrant honeycomb structure and showed that the extent of gradient (i.e., internal angle increment) has significantly affected the properties of the composite gradient sandwich panel and the angle-gradient configuration is inclined to strongly localize the damage surrounding the loaded region.

The realistic honeycomb inherently has defects such as cell irregularity, missing cell walls and disordered when compared to periodic honeycomb structures (Fig. 6). The

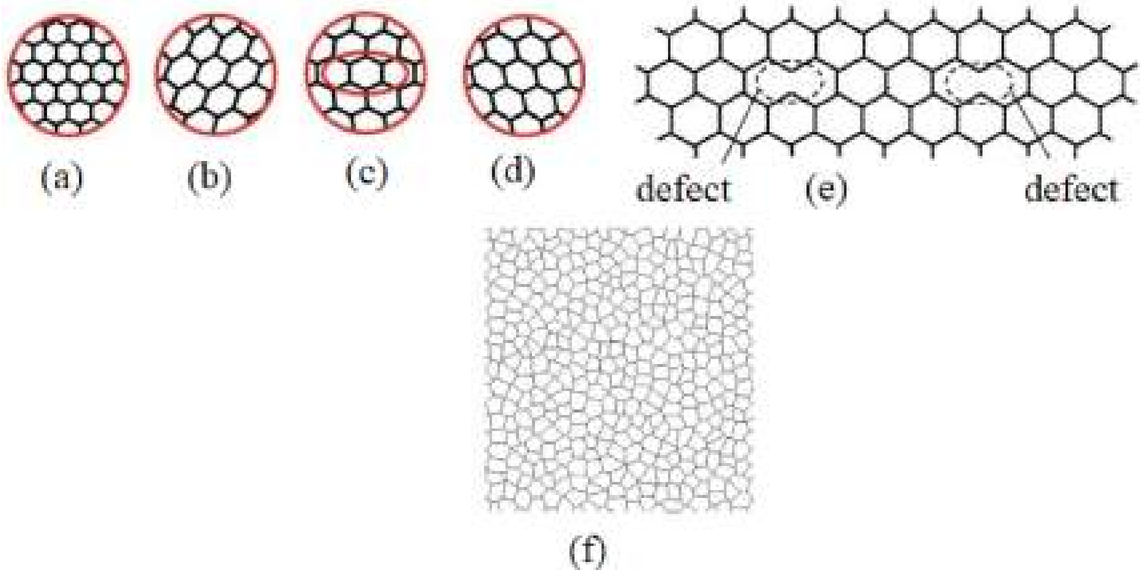

Fig. 6 – A schematic representation of (a–d) normal, left-leaned transition and right-leaned irregularity, (e) missing cell wall and (f) disordered. Reprinted with permission [90,93,94].

missing wall defects can be used to manufacture graded honeycomb structures. In this regard, Fan et al. [87] have reported that the missing-wall defect showed a stronger capacity for energy absorption for positively graded honeycomb than its negative counterpart. In addition, the effect of defect positions on energy-absorbing capacity was decreased by increasing impact velocity. Hu et *al*. [88] have found that the crushing strength of honeycomb structure shows the least sensitivity to impact velocity of 10 m/s and 100 m/s and the cell wall angle of 45° yields the maximum energy-absorbing capacity for both low and high-velocity impact. Yang et al. [89] have compared the energy-absorbing capacity of circular-celled, single-petal and petal-shaped honeycomb structures under impact velocities of 1 m/s and 35 m/s. The LS-DYNA simulation showed a SEA value of 4.12 J/g and 5.52 J/g compared to 2.4 J/g and 3.06 J/g for circular-celled honeycomb, indicating an increase of 71.3% and 80.4%, respectively.

Further, Fan et al. [90] have shown that the larger ratio of missing-wall defects lowered the energy-absorbing capacity. The change in density also can cause gradient properties in the honeycomb structure. In this regard, Zhang et al. [91] have investigated the crashworthiness of graded honeycomb structures in a circle-arc mode. Their results showed that the gradient density had a significant influence on the energy-absorbing capacity of the structure. Ouyang et al. [92] have simulated the octagonal gradient honeycomb structure using missing cell walls to mimic the stress concentration to defect. Their results revealed that the stress concentration is affected by the number of missing cell walls and the aspect ratio.

The double functionally graded structure comprising of functionally graded honeycomb filler and functionally graded thickness tube was found to exhibit superior energy-absorbing capability by increasing crushing displacement. This structure showed a higher energy-absorbing capability than a single functionally graded tube and traditional uniform honeycomb-filled uniform thickness, which was associated with the impact angles [95]. In a different study, de Waal et al. [96] fabricated a graded honeycomb structure using origami and their results showed a decrease in peak force and an increase in energy absorption capacity. These honeycomb-filled structures revealed an increase in energy absorption and load-carrying capability due to the presence of honeycomb filler. Nian et al. [29] have demonstrated the superior energy-absorbing capability of graded circular honeycomb structures through parametric studies and further increased energy absorption by multi-objective optimization. Many structural defects are brought into honeycomb structures during the manufacturing process via conventional methods. This structural defect in a large ratio causes instability in the mechanical behavior of honeycomb structures and reduces the energy-absorbing capabilities in the collision process particularly high-speed ones [93,97]. To this end, the introduction of gradients into the structure can bring difficulties in the manufacturing of such structures. To tackle this, tailoring and foaming technologies, such as tailor welded blank (TWB) [98] and tailor rolling blank (TRB) [99], have been employed to manufacture structures with graded properties. The TWB is a technology by which different materials with different thicknesses can be effectively combined to enhance the crashworthiness of the structures. The TWB uses lasers and electrons to manufacture structures. However, the main shortcoming of this technology is the changes in the thickness between the sections leading to stress concentration. On the other hand, TRB technology can overcome this shortcoming by using a cold rolling mill, which provides a continuous change in thickness [100].

7.2. *Hierarchical honeycomb structures*

Generally, the hierarchical honeycomb structures could be fabricated in different orders. The regular honeycomb structure, which is made up of continuous solid walls and has no

Table 4 – A summary of the comparison between the crashworthiness of regular and hierarchical honeycombs is outlined in the literature.

Material	Type of loading	Structure	Control	Major finding	Ref.
Verowhite	Quasi-static	Square hierarchical honeycomb (SHH)	Regular square honeycomb (RSH)	54.4%, 117.3%, and 126.7% increase in SEA	[103]
AA6061-O	Quasi-static	Second-order hierarchical honeycomb	Regular honeycomb and aluminum foam	2.63 and 4.16 greater plateau stress	[105]
AA3003H18	Dynamic	Horseshoe honeycomb	Triangular, square, hexagonal, and Kagome honeycomb	37%, 38.4%, 6.5%, and 12.4% increase in SEA	[106]
Al6061-T5	Quasi-static	Bionic honeycomb tubular nested structure (BHTMS)	–	29.3 J/g	[52]
AA6060-T4	Quasi-static and dynamic	Self-similar hierarchical honeycomb	Regular honeycomb	Higher plateau stress	[107]
Al6063-T5	Quasi-static	1st, 2nd, 3rd and 4th order hierarchical honeycomb	Regular honeycomb (zero order)	71%, 114%, 201%, and 309% in MCF	[101]
AA3030-H19	Dynamic	1st, 2nd, 2nd, 3rd hexagonal, Kagome and triangular honeycomb	Regular honeycomb	Twice greater EA	[102]
AA6060-T4	Dynamic	1st order and 2nd order hierarchical spider-web	Regular honeycomb (0 order)	62.1% and 82.4% higher SEA	[108]
Solid steel Q235	Quasi-static	Hierarchical lattice tube (HLT) and super hierarchical lattice tube (SHLT)	Single-cell tube (ST)	108% and 176% increase in MCF	[109]
AA3003	Quasi-static	Ripplecomb (corrugated triangular honeycomb)	Regular triangular honeycomb	73.8% increase in SEA	[110]

small-scale hierarchical structure, is in zero order (Table 4). The conventional honeycomb structure is zero-order. The honeycomb structure, which has a small-scale configuration filling or replacing the zero-order honeycomb, is called a first-order hierarchical honeycomb. Finally, if there are two levels of small-scale configurations, in the structure, the hierarchical honeycomb is called a second-order hierarchical honeycomb. Generally, the hierarchical honeycomb structure is made up of a large-scale configuration, in which the small-scale configurations fill the unit cells. The consistent large-scale and small-scale configurations form the self-similar hierarchical honeycomb, while non-consistent configurations form the non-self-similar hierarchical honeycomb [101]. Yin et al. [102] have presented the hierarchical honeycomb structure based on the hexagonal, Kagome and triangular tessellations. The results demonstrated superior performance to regular honeycomb. The energy absorption for hierarchical honeycomb with triangular tessellation was found to be 65 J compared to 34 J and 15 J for Kagome and hexagonal tessellations, respectively, under impact loading with a velocity of 5 m/s. Tao et al. [103] fabricated the square hierarchical honeycombs by replacing each solid cell wall with a smaller square substructure. The results showed a 126.7% increase in SEA compared to regular honeycomb by increasing the number of structural hierarchies under quasi-static loading with a loading rate of 1 mm/min.

Different locations of small configurations, such as vertex, fractal and spider web, can lead to various hierarchical honeycomb structures (Fig. 7). The structural hierarchy can improve the performance of structures and tailor their properties. Wang et al. [104] have studied the effect of the half length of folding on the crashworthiness of double-head and triangular under an impact velocity of 35 m/s. Their results revealed an increase in SEA value from 16.62 J/kg to 17.73 J/g and 24.56 J/g for triangular and double-head honeycombs, respectively, indicating a higher SEA.

Qiao et al. [111] have aimed to enhance the energy-absorbing capacity of a second-order hexagonal honeycomb by adding hierarchy to its structure. The results revealed an enhancement in the collapse stress compared to conventional hexagonal and triangular honeycomb structures, which were more noticeable for low-velocity impact than high-velocity impact.

The vertex-based hierarchy is produced by the replacement of large-scale configurations at the vertices of the structure with small-scale configurations and this can be repeated for higher orders [114]. Tao et al. [115] have replaced the vertex of regular hexagonal and square honeycombs with three small polygon configurations (hexagon, circle and square). Their findings showed an increase of 82.2%, 72.4% and 91.8% in the SEA for joint-to-joint, edge-to-edge and hollow-cylindrical joint hierarchical hexagonal honeycomb structures, respectively, which was higher than regular honeycomb structures under out-plane loading with a velocity of 20 m/s. Similar results were found for hierarchical circular 61.7%, 66% and 75%, but the latter is smaller than the former. Zhang et al. [105] have introduced the triangular configuration of each vertex of a regular hexagonal honeycomb and found the values of SEA as 2.99 J/kg and 2.80 J/kg, 45.99 J/kg under loading for L-direction (in-plane ribbon direction), W-direction (in-plane width) and T-direction (out of plane), respectively, under the loading rate of 5 mm/s showing an increase of 109%, 108% and 34% in SEA, respectively. Also, Sun et al. [113] have designed vertex-based hierarchical honeycomb structures and shown a significant increase of 81.3% and 185.7% in SEA for first-order and second-order hierarchical honeycombs compared to regular honeycombs under the out-of-plane (z-direction) impact velocity of 15 m/s and weight of 400 kg.

The cell-wall-based hierarchy is produced by the replacement of cell walls of large-scale configurations with small configurations. Zhang et al. [105] arranged an array of sub-triangular configurations on the cell wall of a regular triangular honeycomb and showed an increase in the energy absorption of the side hierarchical honeycomb structure, which was mainly attributed to a more stable deformation. The out-of-plane SEA values for ordinary triangular honeycomb, double-triangular honeycomb and side hierarchical honeycomb structures were found to be 5.46 J/g, 3.55 J/g, 9.79 J/g, respectively, under the axial impact of loading with a velocity of 10 m/s and weight of 200 kg. Chen et al. [116] have replaced the cell walls in regular honeycombs with triangular lattice configurations. The results showed the energy absorption was 7.5 times greater than the regular honeycomb structure by adding the hierarchy to the regular honeycomb structure under quasi-static loading with a strain rate of 0.001 s^{-1}.

The fractal-based hierarchy is produced by filling the center of large-scale configurations with similar small-scale configurations. In this regard, Zhang et al. [117] have studied the crashworthiness of triangular, square and hexagonal side fractal thin-walled structures and have found the SEA values were 14.11 J/kg, 12.76 J/kg, 23.90 J/g, respectively, for triangular side, square side fractal and hexagonal side fractal structures under impact loading with a velocity of 10 m/s and weight of 500 kg. Also, the excessive increase in fractal factor changes the folding style from progressive mode to large wavelength which decreases the energy-absorbing capability of the structure. Xu et al. [118] have investigated the crashworthiness of self-similar hierarchical honeycomb structures and found that the size ratio of hierarchy and the impact velocity in the range of 10–30 m/s enhanced the energy absorption of self-similar hierarchical honeycomb compared to the non-hierarchy honeycomb structure. The maximum energy absorption was found to be 428.44 J and 275.76 J for first and second-order hierarchical structures, which was greater than 176.82 J for non-hierarchy honeycomb structures. According to the above-mentioned research, the introduction of structural hierarchy can significantly enhance the energy-absorbing capacity of conventional honeycomb structures. In addition, adjusting the hierarchical parameters, such as the order of small-scale configurations, can improve the energy-absorbing capability of honeycomb structures. Thus, it is vital to accurately understand the energy absorption between the conventional honeycomb and its corresponding small-scale configuration for the promotion of engineering applications such as bumpers and airframes. Nevertheless, it becomes more difficult to manufacture a hierarchical

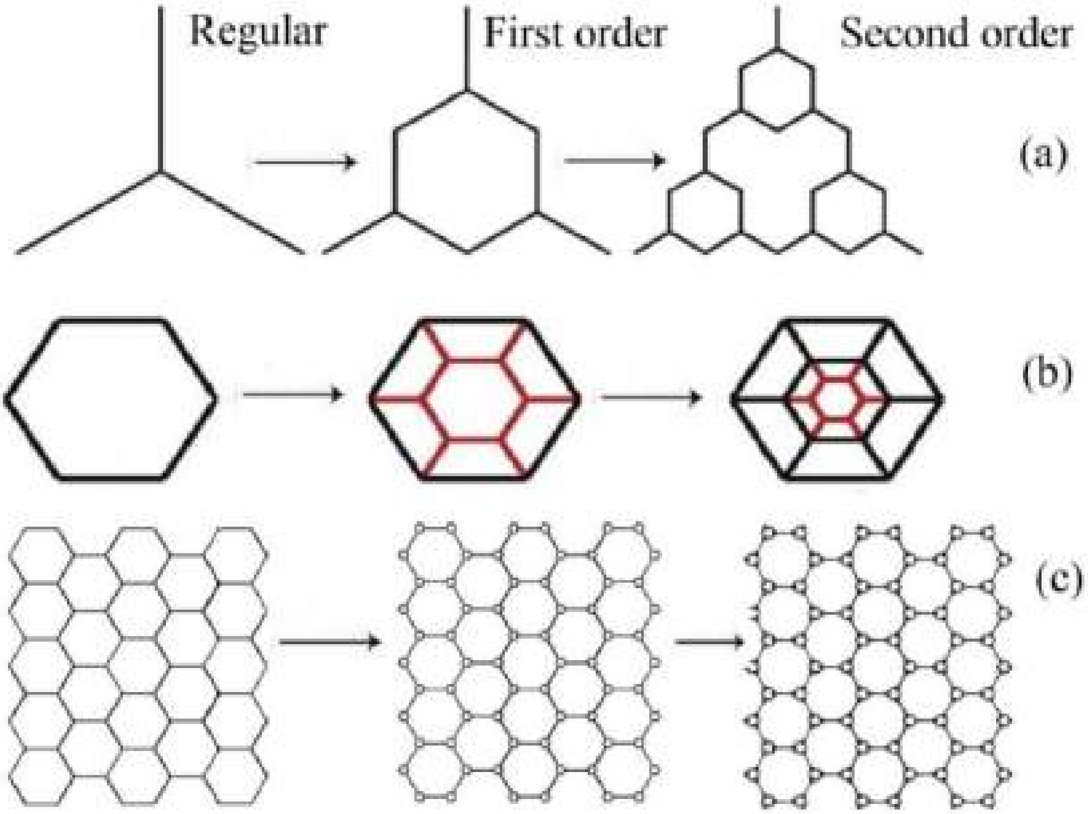

Fig. 7 – A schematic representation of 0^{th} order, 1^{s} and 2nd order (a) fractal (b) spider and (c) vertex honeycomb structure, respectively. Reprinted with permission [101,112,113].

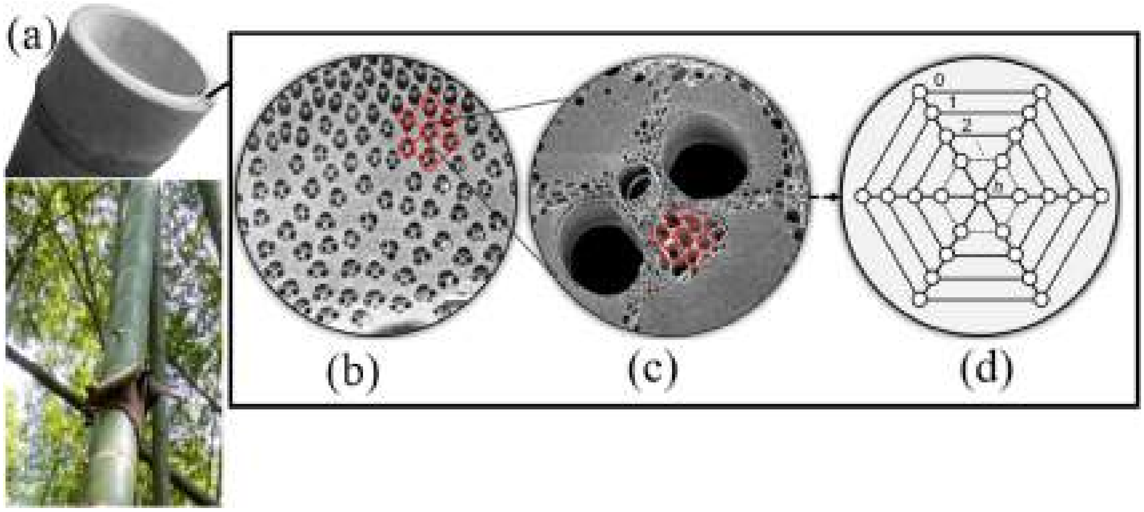

Fig. 8 – (a) *Guadua Angustifolia* bamboo plant and its wall cross-section. (b) Scanning electron microscopy (SEM) micrographs of bamboo culm wall. (c) SEM micrographs of vascular bundles. (d) Bamboo-inspired tubular honeycomb structure. Reprinted with permission [123,125].

honeycomb structure with increasing hierarchy because the main manufacturing process for a hierarchical honeycomb structure is the 3D printing technique. Therefore, a high-precision manufacturing process is required to increase the hierarchical order.

8. Biomimetic-based honeycomb structures

The tubule design is comprised of hollow or flowing channels in similar orientations. This design can be found in bamboo plants and beetle forewings in micro and nanoscale observations. The mechanical properties of these tubules are affected by radius, volume fraction as well as wall thickness. The mechanism of energy absorption in tubule structures includes buckling, bending, collapse and delamination. Furthermore, they enhance the resistance to impact via the deformation and cracking due to the disintegration of the tubule walls. As already mentioned, the honeycomb structure possesses outstanding impact resistance and energy-absorbing capability [20,119]. The focus of following section is to focus on the biomimetic-based honeycomb structures with distinct geometries imitated by natural animals and plants such as pomelo peel [119], bamboo [52], horse hoofs, beetle forewing [121] and spider-web [108] using their natural hierarchical structures.

8.1. *Bamboo plant*

The bamboo plant shows a greater stiffness than metallic materials such as aluminium and steel. Bamboo is a lightweight material that possesses praiseworthy mechanical properties such as high strength and impact resistance [122]. The exertion of the wind force leads to the high bending stress of the bamboo plant. The distinct structure of bamboo comprises a cylindrical column with symmetrical nodes. Besides, its culm is composite with gradient structures which are made up of interconnected channels and multi-cell networks. The high impact resistance capability of bamboo is ascribed to the gradient distribution and the presence of vascular bundles and nodes. This makes it one of the most interesting candidates for thin-walled structural design. The comparable structure and function of the bamboo plant and thin-walled tubes led to the design of thin-walled tubes inspired by bamboo as stated below. Hu et al. [52] have inspired the bamboo tissue to fabricate non-similar nested hierarchical honeycomb structures. The hierarchical honeycomb structure under impact loading with a velocity of 4.4 m/s and a weight of 261.1 kg showed a maximum energy absorption of 35 J/g, which was significantly higher than the traditional metallic honeycomb structure. Zhang et al. [123] have designed a bamboo-inspired tubular honeycomb structure and their findings showed that the energy-absorbing capability of the bio-inspired tubular structure under quasi-static loading with a loading rate of 5 mm/min was affected by coupling effects of structural hierarchy and topological parameters (Fig. 8). Ufodike et al. [124] have designed a functionally-graded honeycomb structure which was inspired by bamboo microstructure. The in-plane compression loading with a loading rate of 5 mm/min on the structure together showed a four times impact energy absorption than that of the graded honeycomb structure. This was ascribed to the variation of density and the uniform distribution of stress throughout the structure.

8.2. *Fruit peel*

The pomelo fruit has a weight of 6 kg and the height of its tree is 15 m, respectively [9]. This causes a large impact on energy dissipation in pomelo upon falling on the ground. This high impact-resistance characteristic of pomelo peel is attributed to its hierarchical organization (Fig. 9). It has three distinct layers, including the exocarp, mesocarp and endocarp. These three layers structure conventionally makes a sandwich structure in which the elastic collapse of a highly porous mesocarp can absorb the strain energy [126]. A significant amount of energy is absorbed via the pore collapse and the peel is damaged only after the compaction of the pores. This structure can endure the high strain and spread the impact all over the porous network when it is collapsed. This enables the pomelo peel to resist impact energies up to 1.5 kJ [126]. Zhang et al. [120] have designed a hierarchical honeycomb inspired by pomelo peel. The hierarchical honeycomb under uniaxial compression loading with a rate of 5 mm/min showed an increase in SEA, which was 1.5 times greater than traditional honeycombs both out-plane and in-plane due to the increase in the structural hierarchy and different geometrical dimensions. Also, Yang et al. [127] have designed a porous structure inspired by pomelo peel for impact energy absorption. The pomelo-peel-inspired structure showed a SEA of 12.94 J/g, which was higher than that of 10.21 J/g, 11.92 J/g and 10.89 J/g for homogenous, one-end gradient cube and both-end gradient, respectively, under quasi-static loading with loading rate of 0.02 mm/min. The durian shell is also another source of bioinspiration to design energy-absorbing structures in which thorns and mesocarp play a key role in energy absorption [128]. The durian shell can provide effective impact energy absorption when falling from its 12 m tree. Ha et al. [129] have found a more effective impact energy absorption for durian shells along lateral direction compared to that of axial counterpart. This was due to the orientation of fibers. The quasi-static loading was conducted using 50 kN loading and a strain rate of $2 \times 10^{-3}\ s^{-1}$. The SEA of thorns was found to be 0.38 J/g, which is greater than that of 0.19 J/g for mesocarp under axial loading. However, half-shell durian revealed a SEA of 390 J/g.

8.3. Plant stem

The plant stem naturally has a hierarchical configuration in which the honeycomb-like core is introduced into its tubular structure (Fig. 10). In this regard, Chen et al. [130] have inspired the grassy stem to design a hierarchical honeycomb structure. They have used a top-bottom approach and showed an increase in the SEA by increasing the hierarchical level *n*. Fang et al. [131] have replaced the sides of the hexagon with smaller hexagons in a bioinspired grass stem honeycomb structure. The results revealed that applying this hierarchy to the honeycomb structure enhanced the plateau stress, which was 2.63 times greater than the regular honeycomb. This was attributed to the increase in the ratio of thickness to cell-edge length. The quasi-static loading with a loading rate of 2 mm/min was applied to the structure. Also, Ha et al. [132] designed the hierarchical circular honeycomb design with the inspiration of natural wood. The nature-inspired hierarchical honeycomb structure under quasi-static compression loading

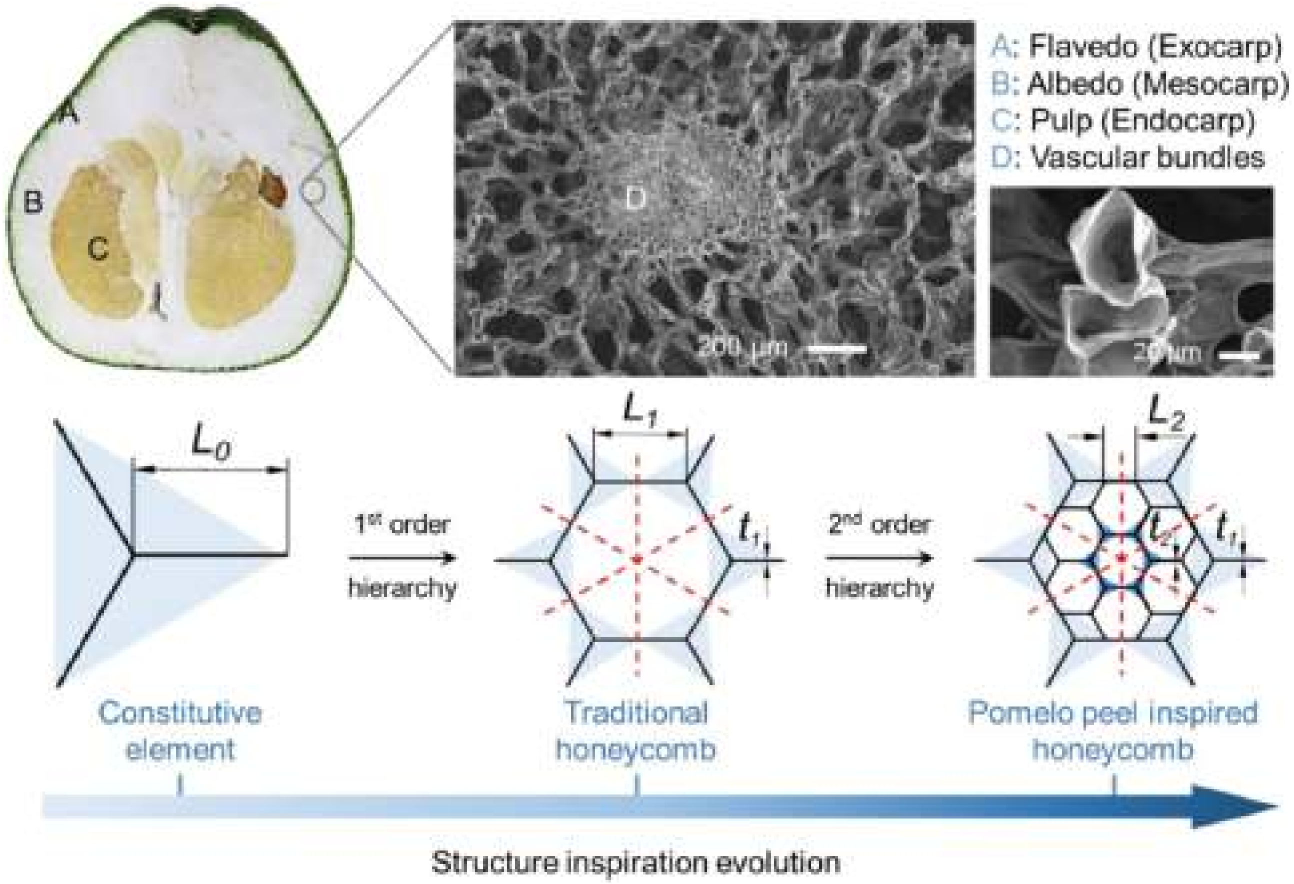

Fig. 9 – SEM photographs for detailed microstructures of typical pomelo peel (A, B, C and D represent flavedo, albedo, pulp and vascular bundles, respectively), together with configurations of pomelo peel-inspired hierarchical honeycomb. Reprinted with permission [120].

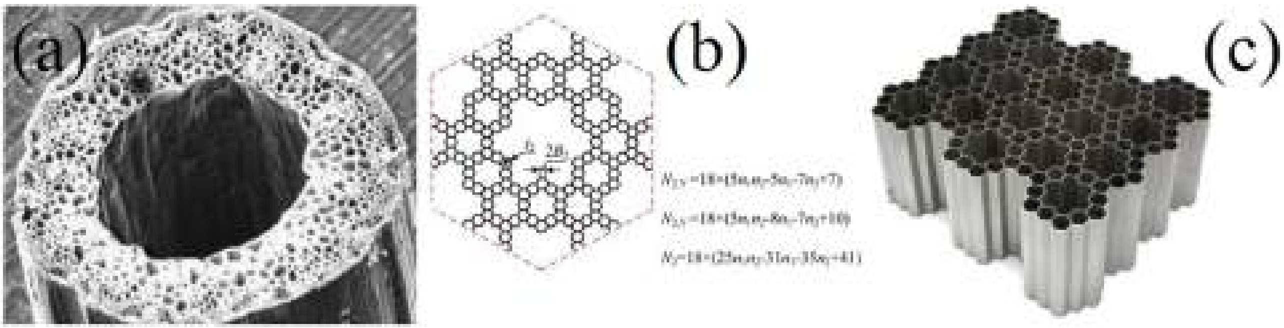

Fig. 10 – Natural hierarchical structure. (a) SEM photographs for the grassy stem, (b) second-order hierarchical honeycomb structure, (c) hierarchical honeycomb structure specimen. Reprinted with permission [131,133].

with a loading rate of 5 mm/min showed higher SEA compared to conventional honeycomb. The SEA values were increased from 6.7 J/g to 8.82 J/g indicating, an increase of 31.64%.

8.4. *Beetle elytra*

The beetle elytra are rigid and lightweight and can efficiently protect the beetles from external impact loadings. For instance, they can tolerate a punch load up to 23 N [134]. This high mechanical property may be ascribed to irregular cellular patterns with hollow pillars on the walls and intersections of elytra [135]. Further, the trabecular structure between different laminas of elytra strengthens the beetle forewing. The comprehensive understanding of the internal microstructure of the beetle elytra led to the design of beetle-based biomimetic energy-absorbing structures. Wang et al. [136] have fabricated a lattice structure inspired by the configuration of the beetle forewing and arranged it into a honeycomb structure (Fig. 11). The bio-inspired structure under dynamic loading of Split Hopkinson Pressure Bar with a strain rate of 10^2 and 10^4 s^{-1} was found to be affected by printing parameters and showed a maximum SEA of 9.088 J/g. Additionally, an increase of 90.8% was found for dynamic loading rates in the range of 0.0005/s and 1000/s.

Hao et al. [137] have also inspired beetle elytra to manufacture honeycomb column thin-walled structures by locating the hollow columns on the walls, wall junctions and both on walls and junctions. It was found that thin-walled structures with filled columns showed better energy absorption than honeycomb structures in which the diameter of the column affected the energy absorption. The axial impact loading with a velocity of 10 m/s demonstrated a better SEA with a column diameter of 16 mm (29.73 J/g and 29.26 J/g).

Xiang et al. [138] have designed circular tubes comprising different polygon cross-sections inspired by lady beetle forewing. The regular hexagonal honeycomb structure under axial impact loading with a weight of 500 kg and velocity of 10 m/s showed a significant SEA for the tubes, with diameters in the range of 18.13 mm and 23.56 mm. Xiang et al. [139] have designed multi-cell tubes comprising honeycomb and circular tubes inspired by ladybeetle. In this structure, the circular tubes were located at the center of the walls of the honeycomb. The axial impact loading with a weight of 100 kg and a speed of 10 m/s demonstrated a higher SEA compared to the traditional aluminium honeycomb structure. Zhang et al. [140] have designed multicellular tubes inspired by beetle forewings with quadrilateral, hexagonal and octagon cross sections. The axial impact loading with a velocity of 10 m/s

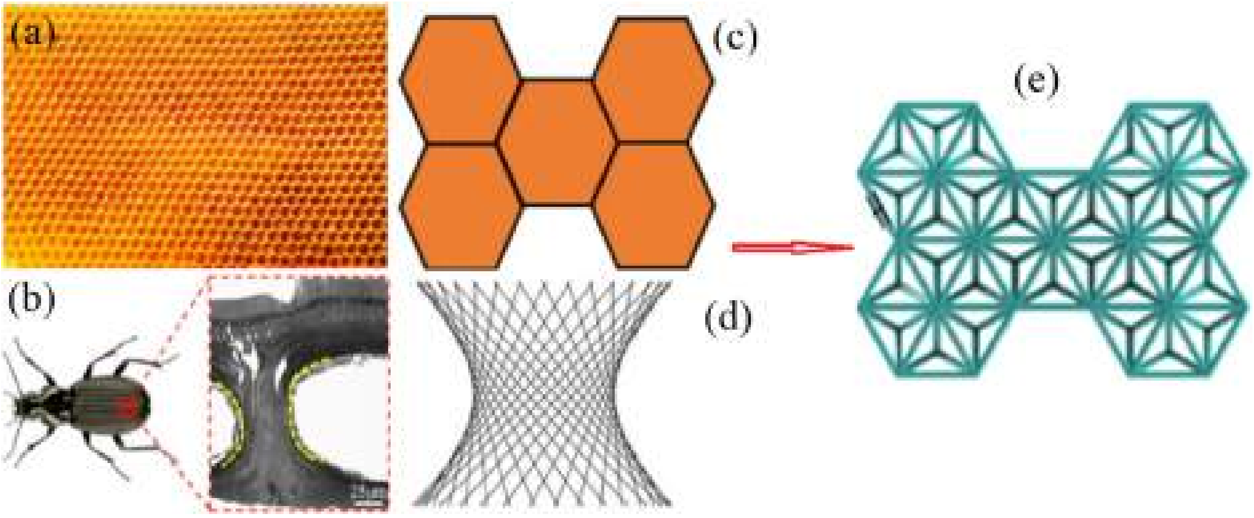

Fig. 11 – Fabrication of biomimetic lattice structure (a,c), honeycomb structure (b,d), the microstructure of beetle front wing and (e) lattice structure. Reprinted with permission [136].

showed the highest SEA of 36.09 J/g for octagonal cross section compared to that 29.94 J/kg for quadrilateral, and 33.86 J/g for hexagonal, respectively. All the multicellular tubes showed a higher SEA than that of 22.99 J/g for designs without tubes. Du et al. [141] have introduced filling cellular structures with different orders of hierarchy and investigated the energy absorption under impact loading with a velocity of 10 m/s and a weight of 500 kg. Their findings showed SEA values of 21.88 J/g and 28.45 J/g for the first- and second-order hierarchy. The enhancement in the energy-absorbing capacity is ascribed to the increase in the number of connections inside the bio-inspired structures providing an extrusion effect and producing a more stable buckling mode (Fig. 12).

Yu et al. [142] have manufactured a crash box by inspiring an end-trabecular beetle elytron sandwich plate. The energy absorbed by the conventional crash box and elytra-based trabecular honeycomb was found to be 75.6 J and 375.5 J, respectively, indicating a 5 times greater energy absorption for elytra-based trabecular under compression with a loading rate of 1 mm/min. Du et al. [143] have investigated the energy-absorbing capacity of beetle elytra-inspired honeycomb thin-walled structures with different topological structures including circular, hexagon octagon and triangle. Their findings showed that the hexagon and octagon configurations showed excellent energy-absorbing capability under the velocity of 10 m/s and weight of 400 kg due to the production of more uniform folds compared to circular and triangle counterparts with poor energy absorption.

8.5. *Spider web*

The spider web was also a source of inspiration for designing hierarchical structures. In this regard, Zhang et al. [144] have inspired the spider web and presented a fractal hierarchical hexagon. The computational results revealed that both hierarchical and fractal structures significantly enhanced the energy absorption compared to single-wall non-hierarchical structures. Also, fractal configuration and order can significantly affect the energy absorption of hierarchical structures. The second-order fractal hierarchical structures were found as the optimal design. He et al. [108] have introduced the spider web hierarchy into the honeycomb structure. The first-order and second-order spider web hierarchical honeycomb structure under impact loading using a weight of 400 kg and a velocity of 15 m/s showed an increase of 62.1% and 82.4% in SEA compared to the regular honeycomb structure, which can be ascribed to an increase in density of the structure (Fig. 13).

8.6. *Woodpeckers*

The woodpeckers can exceptionally mitigate the shock during rhythmic drumming using their beaks. The speed of the repeated impact during pecking is approximately in the range of 6–7 m/s, nonetheless their head is not injured after the impact [145]. This remarkable impact-resistant capability in woodpeckers is ascribed to the tightly packed wavy

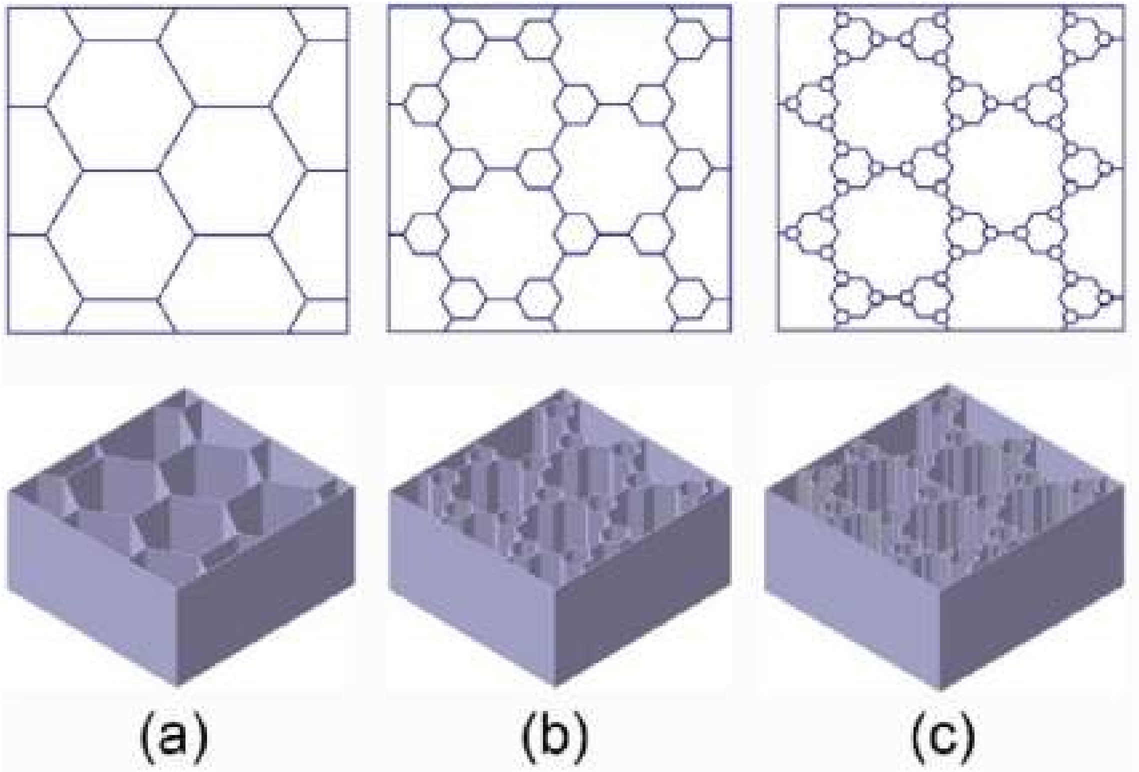

Fig. 12 – Different types of biomimetic structures: (a) original honeycomb, (b) first-order hierarchy and (c) second-order hierarchy. Reprinted with permission [141].

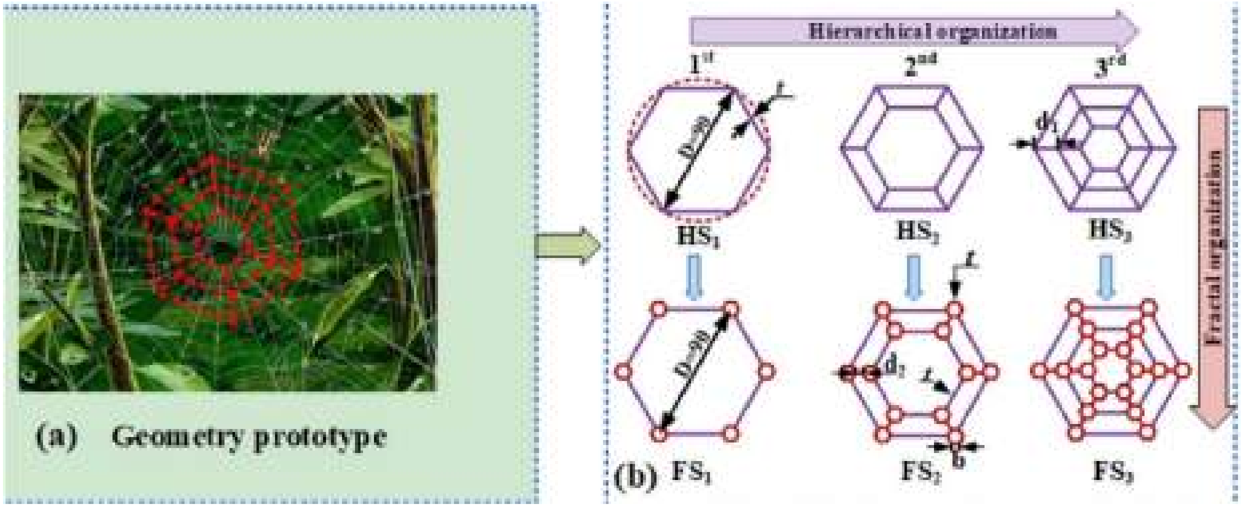

Fig. 13 – Natural hierarchical structure: (a) natural spider web, (b) hierarchical and fractal honeycomb structure. Reprinted with permission [144].

configuration, which is found at the grain boundaries admitting local shearing. The upper beak of the woodpecker possesses a honeycomb structure. However, the cell walls of this honeycomb have a sinusoidal structure, unlike the traditional honeycomb. The energy-absorbing performance can be enhanced by this wavy structure. This high impact resistance makes them suitable to design energy-absorbing structures (Fig. 14). Ha et al. [58] have inspired the microstructure of the woodpecker beak to construct the bioinspired honeycomb sandwich panel. The bioinspired sandwich panel under compression loading with a constant speed of 10 m/s in the out-of-plane direction revealed that the SEA of the panels was 125% and 67% greater than that of a conventional honeycomb sandwich panel with a similar thickness core. The reason is that the energy absorption in the honeycomb is only through the buckling of cell walls while the nature-bioinspired wavy honeycomb is buckled and bent at the peak of the wave allowing plastic deformation without any catastrophic failure. Additionally, the energy absorption was found to be tailorable by the adjustment of wave number and amplitude. Further, the increase in wave number, amplitude and core thickness also enhanced the SEA.

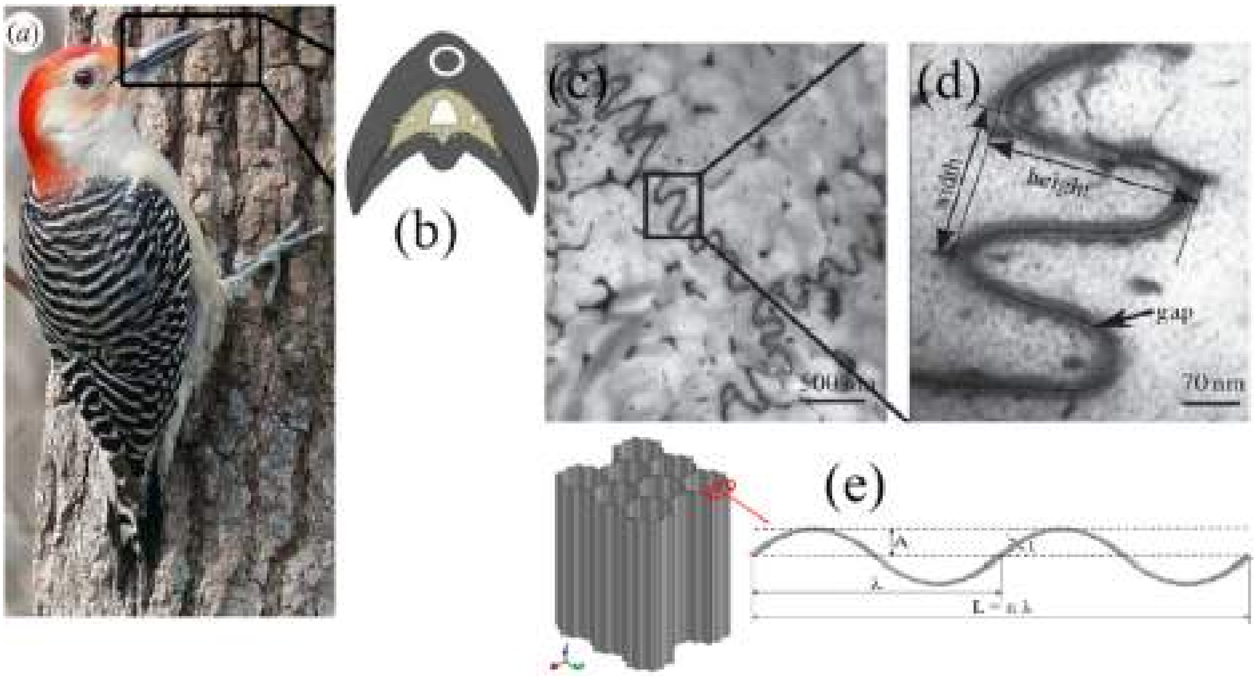

Fig. 14 – (a) Red-bellied woodpecker, (b) wavy structure of its beak, (c and d) transmission electron microscopy (TEM) micrographs of the beak and (e) wavy honeycomb inspired by woodpecker beak. Reprinted with permission [146,147].

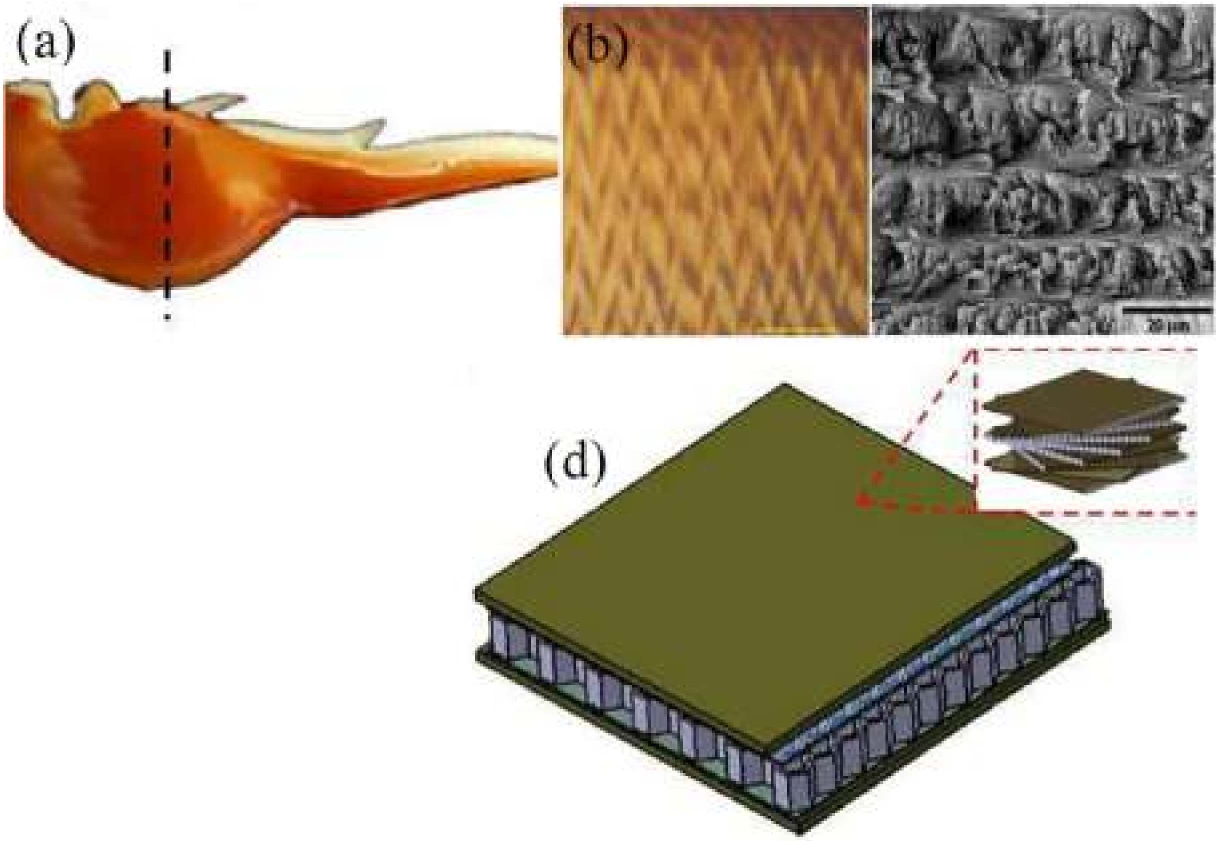

Fig. 15 – (a) Mantis shrimp (b) dactyl club, (c) SEM of the periodic region in dactyl club, (d) and dactyl-based honeycomb sandwich panel Reprinted with permission [150,152].

8.7. *Shrimp dactyl*

The peacock mantis shrimp can produce acceleration and impact speeds of 10^5 m^2/s and 20 m/s, respectively. This shows one of the most impact-resistant structures in nature [148]. This high mechanical property is attributed to the crack deflection and twisting, as well as the presence of herringbone architecture [149]. Han et al. [150] have fabricated the sinusoidal-corrugated helicoidal honeycomb sandwich panel by the combination of helicoidal periodic region and herringbone architecture. The low-velocity impact loading with a weight of 3 kg and 12.63 J impact energy on the structure was found to enhance the resistance to damage compared to traditional unidirectional skin sandwich-structural honeycomb (Fig. 15). Similarly, Han et al. [151] have fabricated the sinusoidal-corrugated helicoidal honeycomb sandwich panel by the combination of helicoidal periodic region and herringbone architecture. The low-velocity impact loading with a weight of 3 kg and 12.63 J impact energy on the structure revealed an increase of 106.0% in the average impact force compared to the unidirectional skin sandwich-structural honeycomb. This indicated the improved impact resistance.

8.8. *Horse hoof*

The horse hooves are porous structures that possess promising energy-absorbing capacity due to their sustainability under high-impact circumstances. Yang et al. [106] have added the horseshoe mesostructure to the regular triangular, square, hexagonal and Kagome honeycomb. The honeycomb structure comprising horseshoes under out-of-plane uniform compression with a velocity of 1 m/s showed a significant increase in the SEA compared to the conventional honeycomb structure which was attributed to the increased plateau region (Fig. 16). The SEA was found to be 9.80 J/g, 8.25 J/g, 7.47 J/g and 8.03 J/g for Kagome, hexagonal, square and triangular honeycomb structure, respectively.

9. Sandwich panels

The sandwich structures frequently have porous characteristics due to the presence of cellular cores with complex topologies. Therefore, one of the commonly used engineering structures for energy absorption in the automotive industry is the sandwich structure as they possess a high ratio of flexural stiffness to weight as well as excellent energy-absorbing capability. In the sandwich panel, the energy is dissipated through the core and the cracks are inhibited. The prevention of catastrophic failure under impact loading is the final purpose of using sandwich structures. The cellular core could be found in the form of a honeycomb. The sandwich structure is comprised of an inner layer (core) and two outer layers (face sheet). The inner layer is softer with more flexibility while the

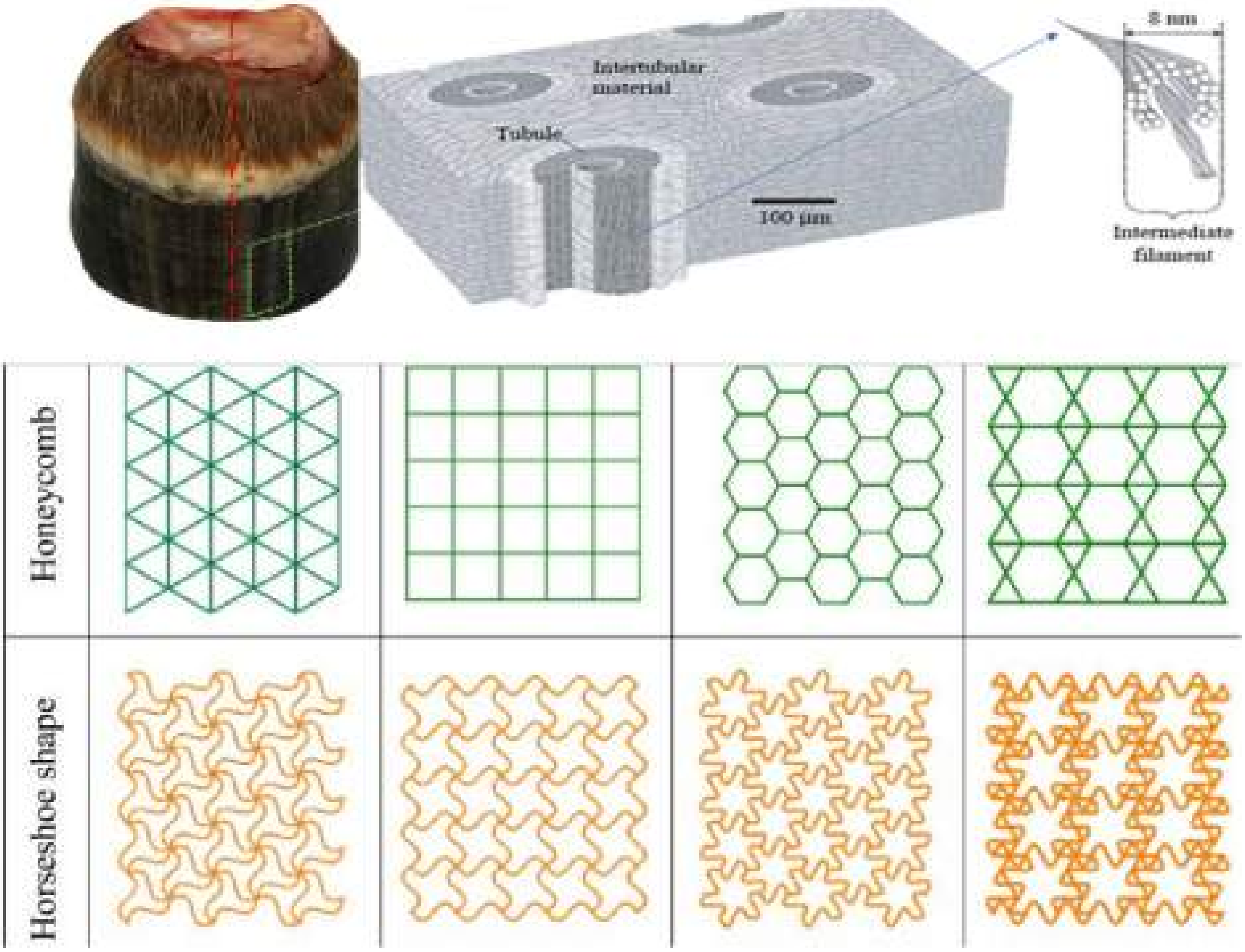

Fig. 16 – (a) Natural horse hoof, (b) tubules and intratubular structure of horse hoof, (c) horse hoof-inspired honeycomb structure with triangle, square, hexagon and Kagome cross sections. Reprinted with permission [106,153,154].

two faces are stronger with more rigidity [150]. The face sheets in this sandwich panel are typically made up of metals such as aluminium or stainless steel or fiber composite as the face sheets. Aluminum and polymeric papers are commonly used for honeycomb cores. A typical honeycomb sandwich panel is illustrated in Fig. 17.

The damage mechanism of sandwich panels under impact loading is comprised of local buckling of the core wall, face sheet yielding and core shearing playing an important role in the energy absorption capability of the structure [56,157]. The mechanisms of impact energy absorption in sandwich panels strongly rely on the geometry and properties of the face sheet and the core materials [158]. The deformation of the core in the sandwich structure plays the principal role in energy absorption [159]. The metallic sandwich structures have been widely used in recent years due to their plastic deformation, which can absorb impact energy during a crash. The crashworthiness of sandwich panels has been enhanced by the replacement of porous cores such as honeycombs [160]. The sandwich panels with porous honeycomb cores have distinct advantages [161,162]; however, consideration of certain restrictions is necessary. For instance, the bonding faces of sandwich panels completely cover the honeycomb accommodating water and vapor. This leads to the deterioration of mechanical performance as well as an increase in the weight of the structure [163]. The design core inspired by nature is summarized in the following section. Solak et al. [164] have designed a wavy honeycomb sandwich panel and their findings revealed an increase of 7–110% in SEA compared to that of the ordinary flat-walled sandwich structure. The SEA was also increased by increasing wave amplitude and wavenumber. Nonetheless, the optimization of the values of mechanical performance and weight gain is vital.

The upper and lower skins in *dichotoma* beetle are sandwiching a trabecular-honeycomb structure. In this regard, Chen et al. [121] have investigated the energy-absorbing capability of beetle elytra-inspired sandwich panels under a loading rate of 1 mm/min. The results showed that the energy absorption of beetle elytra-inspired sandwich panels and honeycomb plates was 5.8 MJ/m^3 and 2.7 MJ/m^3, respectively, showing an increase of 115% in energy absorption compared to honeycomb plates. This was due to the prevention of complete failure of honeycomb walls and trabeculae and jointly bearing the vertical load (Fig. 18).

The beetle forewing was inspired to construct the bio-inspired sandwich panel using aluminium honeycomb as the

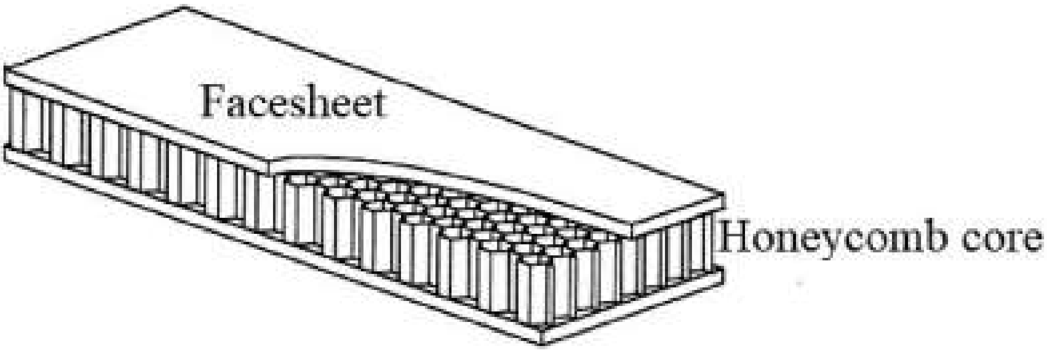

Fig. 17 – A schematic representation of a honeycomb sandwich panel. Reprinted with permission [156].

core and carbon-reinforced plastic as the plates at the top and bottom of the structure [166]. The results demonstrated higher energy absorption and lower peak force compared to carbon-reinforced plastic. The leaf of plants in nature can efficiently withstand long-term alternating stress which is caused by wind and rain. The mechanism of stress-resistance of plant leaves can be ascribed to the reorientation of the vascular vein throughout the growing process [167]. Sun et al. [168] reinforced the porous honeycomb core with grit (lattice) and designed the sandwich panel. The sandwich panel is under quasi-static loading with a loading rate of 10 mm/min. The energy absorption of grit-reinforced honeycomb core sandwich panels was 151 J, which was higher than that of 136 J and 31 J for honeycomb and grid core sandwich panels alone, respectively. Nian et al. [29] have fabricated a nature-inspired functionally graded honeycomb core with circular tubes by inspiration from a natural functionally graded structure, such as a horse hoof and bamboo stem. Their findings showed the SEA of graded honeycomb-filled circular tubes was improved by 89.73% and 23.68%, respectively. The findings in the open literature can give a valuable understanding of the structural design of sandwich panels in the future for various engineering applications. The purpose of inspiration from nature is to achieve excellent structures with high-impact energy absorption to meet the requirements for engineering applications. A comparison between the impact energy-absorbing capacity of nature-inspired design and the hexagonal aluminum honeycombs and metallic foams.

10. Manufacturing techniques

Different ways have been utilized to manufacture the honeycomb structures including adhesive bonding [69], resistant welding [169], diffusion bonding [170], brazing diffusion [171], thermal diffusion [172] as well as expansion and corrugation techniques [173]. Regardless of manufacturing technique, a single block of honeycomb possesses a weak energy-absorbing ability, which is far from the requirement for extreme dynamic conditions such as high-speed train crashes, etc. For example, a honeycomb energy absorber needs to show massive dissipation of kinetic energy during train collision operation at a high speed of around 200 km/h. The fabrication of complicated biomimetic-based structures is difficult for the conventional manufacturing process. In conventional techniques, the structure is manufactured by the subtraction of materials from the workpiece [174]. Nonetheless, the additive manufacturing (AM) process can offer methods that are capable of manufacturing the detailed nature-inspired structure. The reaction of biological structures to the exterior forces as well as the internal mechanics can be studied by AM methods [175]. In the AM manufacturing techniques, the overall structure is built by the connection of materials using the utilization of a layer-by-layer approach. The commonly-used AM techniques are material extrusion, material jetting, powder-bed fusion, vat polymerization and binder jetting. Several AM techniques have been utilized to create nature-inspired structures, as previously reviewed by other authors [25,175–178].

10.1. *Material extrusion*

Material extrusion is extensively utilized as the AM technique in which the three-dimensional (3D) object is created by the continuous passing of material through a heated nozzle followed by deposition in a layer-by-layer formation. The focus of this process is on the thermoplasticity of the polymer filament, which let fusing during printing and hardening at room temperature. The impact properties of the prototype fabricated by this method are affected by the thickness of the layer and the orientation of filaments [179]. This straightforward and cost-effective AM technique is suitable for the fabrication of prototypes of different sizes and shapes. Besides, the final prototype can be fabricated by using various thermoplastic materials [180]. This technique has been investigated to enhance the design of porotype for energy absorption [181]. Nonetheless, the distortion of the interlayer weakens the mechanical properties of the printed prototype [182]. The lightweight impact-resistant nature-inspired structures have been fabricated by the dual material extrusion process. Soft and rigid materials can be integrated into a single structure similar to many natural structures by using multi-material printing. However, there are some restrictions related to this technique that yet needs addressing such as a slow rate of printing and poor surface quality.

10.2. *Material jetting*

The materials jetting is another AM technique, in which the photopolymer resin is sprayed in droplets and is thereafter cured by using ultraviolet (UV) light. This technique is similar to 2D inkjet printing; thus it is also referred to as 3D inkjet printing [183]. The disadvantages of this technique are its expensiveness and the involvement of photosensitive materials that may compromise the quality of the final prototype due to the inattentive curing. Besides, the final prototype needs post-processing, which increases the production time [184].

10.3. *Powder bed fusion*

Powder bed fusion is one of the AM techniques in which the powders are melted and fused in each layer using an electron or laser beam or binder. In this technique, the 3D final prototype is fabricated by rolling the consecutive layers of powder on top of the preceding layer and their subsequent fusing. Subsequently, fine powders are closely packed on the platform with even distribution forming thin layers. Finally, the surplus powder is eliminated and other processing such as coating and infiltration is carried out on the final prototype. The use of a powder bed as the support is the key advantage of this technique as the need for removing the supporting material is eliminated. However, this technique is expensive and time-consuming as it needs post-processing. Besides, the fusion with binder leads to undesirable properties due to the presence of high porosity. The beetle-inspired honeycomb structure has been fabricated by powder bed diffusion [185].

Although the design of nature-inspired structures by AM techniques is promising and can pave effective ways to design and fabricate the next generation of lightweight structures for energy-absorbing applications; however, the AM machines that are currently available cannot fabricate the structures from the nano-to-macro scale. The above-mentioned techniques are capable of creating structures with complex geometries. However, a detailed design smaller than 1 μm cannot be created using these AM techniques. Additionally, the susceptibility of AM-made porotypes to fatigue damage is another critical challenge. This is attributed to the poor geometrical accuracy and porous architecture, which further weaken the structure [186]. Due to these restrictions mentioned above, the current restrictions of AM techniques should be identified and extended in future studies for optimal replication of intricate biological architectures. The AM techniques for the fabrication of nature-inspired structures are depicted in Fig. 19.

11. Concluding remarks and future direction

Nature has shown pleasingly organized structures, which possess an excellent energy-absorbing capacity. These interesting structures are found in nature and have undergone an evolutionary process over a long period. The researcher can use these structures as a source of inspiration to get practical novel ideas to design highly-impact resistant structures. This review paper aims to establish a relationship between nature-inspired structural design (particularly honeycomb) and their capacity to absorb energy and to provide guidelines to develop impact-resistive structures. The advanced honeycomb designs, including hierarchical, functionally gradient and sandwich structures, were found to increase the energy-absorbing capabilities of the conventional honeycomb structures by reviewing several research papers in the literature. Additionally, the different biomimetic-based honeycomb structures inspired by different species were highlighted in this review. The conventional cellular structures comprising such traditional honeycomb and metallic foams usually show a SEA of 10 J/g or below [188,189]. However, the SEA of nature-inspired honeycomb structures can reach the value of 35 for bamboo-inspired honeycomb structures, which reveals the superior energy-absorbing capacity of nature-inspired honeycomb structures. Finally, a discussion on the AM techniques for the fabrication of nature-inspired structures was also provided together with a listing of the advantages and disadvantages of each technique.

Machine learning (ML) is known as a powerful tool to guide the design of impact-resistant structures by the sufficient gathering of data and reducing the cost of computation. The particular relationship between the single critical characteristic and mechanical properties of nature-inspired structures can be illuminated by ML. Also, the extraction of

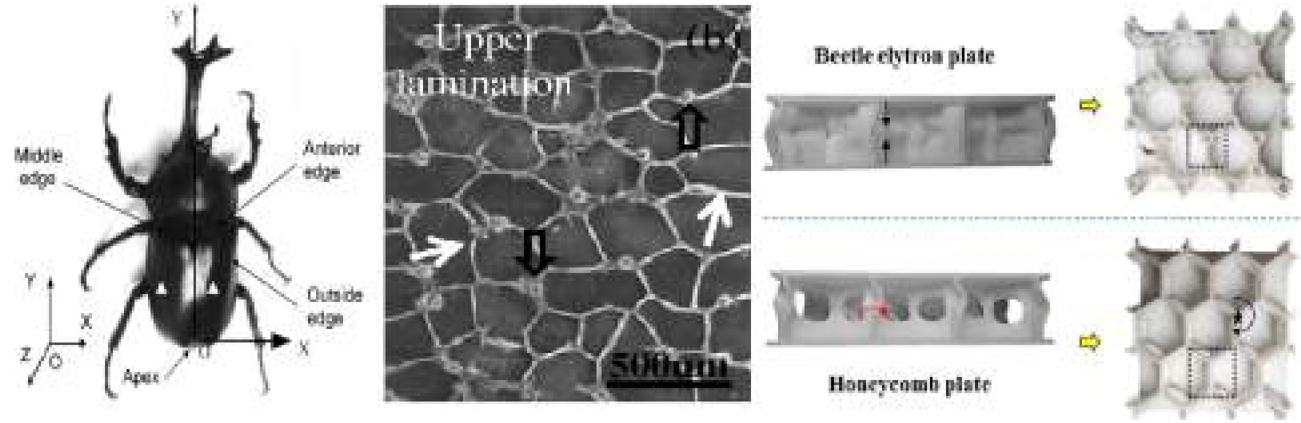

Fig. 18 – Microstructure of adult *Allomyrina Dichotoma* beetle elytra and the corresponding plate. Reprinted with permission [121,165].

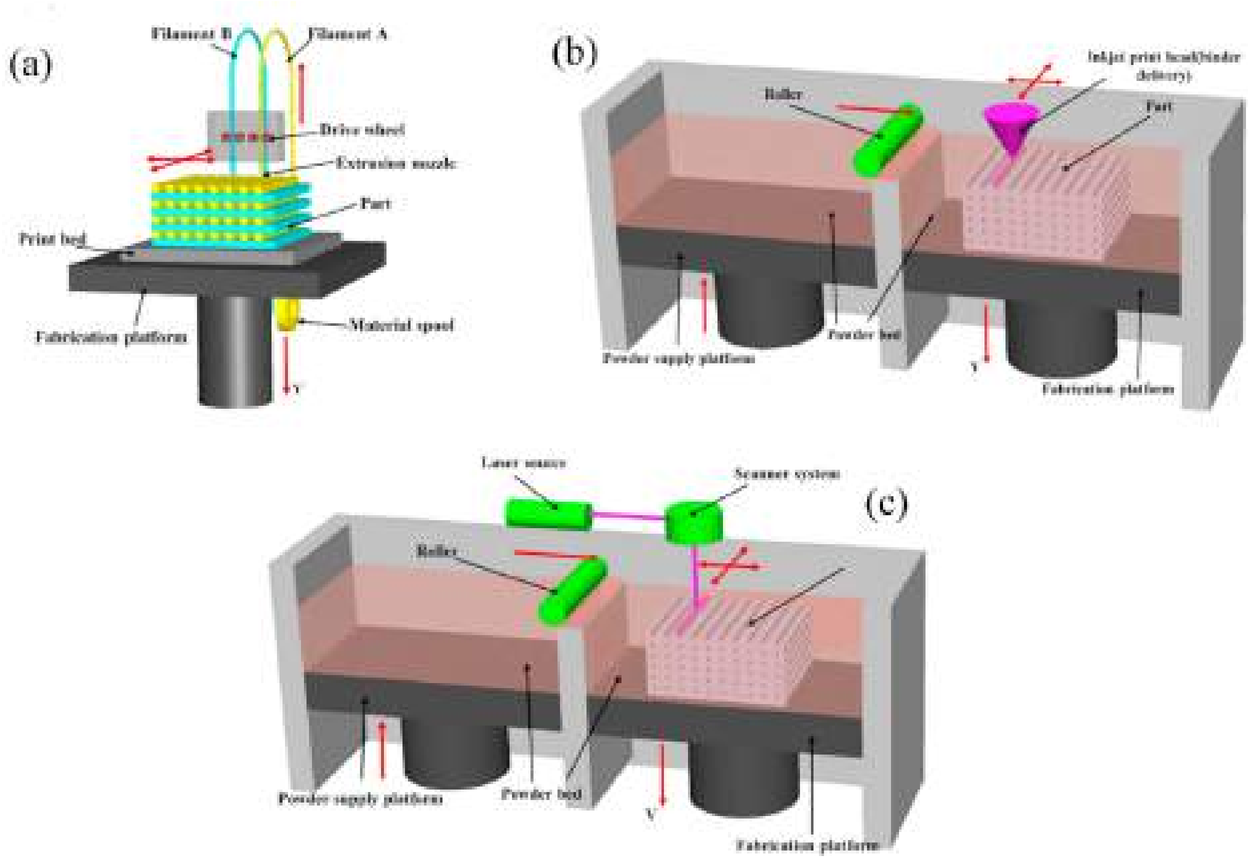

Fig. 19 – A schematic representation of AM techniques to fabricate nature-inspired structures: (a) material extrusion, (b) material jetting, and (c) powder bed fusion. Reprinted with permission [187].

critical structural characteristics from geometric parameters can play a key role in optimizing nature-inspired structures with desirable mechanical performance. Although ML has widely been used in various fields of engineering, the research which focuses on the implementation of ML in nature-inspired structures is restricted in the literature. For example, the feasibility of ML in studying the effect of design parameters on the performance of wavy honeycomb inspired by woodpeckers was proven [164]. Thus, the ML-assisted design of nature-inspired architectures as mentioned in this review is still open and can be further explored.

One of the challenges here is to explore the deformation and energy absorption of these honeycomb-based structures using advanced manufacturing techniques, proper mechanical testing and modelling. Manufacturing technology is a key factor that limits the development of advanced honeycomb-based structures. The manufacturing technology should overwhelm the geometric complexity of high-order honeycomb-based structures and should be highly precise and low-cost. Thus, economic and effective manufacturing technology should be further developed. Further, more theoretical models should be developed to give a better understanding of the mechanisms involved in the enhanced crashworthiness of honeycomb-based structures. Finally, the combinatory effect of honeycomb structures on crashworthiness needs to be explored such as hierarchical with graded honeycomb structures under different loading conditions. Additionally, 3D cellular structures are required to be developed based on the honeycomb configurations with enhanced crashworthiness under multiple loads and directions. In conclusion, it is expected that the advanced honeycomb-based structures open a new window into the era of multifunctional lighter and stronger materials for transportation.

Authors contributions

Conceptualisation, investigation, methodology, data curation and writing—original draft and preparation, were performed by *H.M., Z.A., and* S·S.R.K. Validation, visualization, formal analysis, acquisition and writing—review and editing, were performed by *H.M., Z.A., M.P., S.A.M., M.A.F.J., H·H., and* S·S.R.K. Supervision were performed by *H.M., and Z.A.* Resources, funding, and project administrations were supported by *Z.A., M.P., and* S·S.R.K. All authors have read and agreed to the latest version of the article.

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.

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REFERENCES

[1] W.H. Organization, Global status report on road safety 2015, World Health Organization2018.
[2] Kucera L, Gajdosik T, Gajdac I, Mruzek M, Tomasikova M. Simulation of real driving cycles of electric cars in laboratory conditions. Commun - Sci Letters Univer Žilina 2017;19(2):42–7.
[3] Wong KJ, Johar M, Koloor SSR, Petrů M, Tamin MN. Moisture absorption effects on mode II delamination of carbon/epoxy composites. Polymers 2020;12(9):2162.
[4] Mlýnek Jaroslav, Petrů Michal, Martinec Tomáš, Rahimian Koloor Seyed Saeid. Fabrication of high-quality polymer composite frame by a new method of fiber winding process. Polymers 2020;12(5):1037.
[5] Joshani M, Koloor SSR, Abdullah R. Damage mechanics model for fracture process of steel-concrete composite slabs. Appl Mech Mater 2012;165:339–45 [Trans Tech Publications Ltd].
[6] Koloor R, S S, Karimzadeh A, Abdullah MR, Petrů M, Yidris N, et al. Linear-nonlinear stiffness responses of carbon fiber-reinforced polymer composite materials and structures: a numerical study. Polymers 2021;13(3):344.
[7] Xia Z. Biomimetic principles and design of advanced engineering materials. John Wiley & Sons; 2016.
[8] Wallat L, Selzer M, Wasmuth U, Poehler F, Nestler B. Energy absorption capability of graded and non-graded sheet-based gyroid structures fabricated by microcast processing. J Mater Res Technol 2022;21:1798–810.
[9] Morton JF. Fruits of warm climates. JF Morton; 1987.
[10] Wang M, Zhang J, Wang W, Gao L. Compression behaviors of the bio-inspired hierarchical lattice structure with improved mechanical properties and energy absorption capacity. J Mater Res Technol 2022;17:2755–71.
[11] Yao S, Swetha P, Zhu Y. Nanomaterial-enabled wearable sensors for healthcare. Advanced healthcare materials 2018;7(1):1700889.
[12] Huang H, Dong Y, Wan S, Shen J, Li C, Han L, et al. A transient dual-type sensor based on MXene/cellulose nanofibers composite for intelligent sedentary and sitting postures monitoring. Carbon 2022;200:327–36.
[13] Shan C, Che M, Cholewinski A, Ki Kunihiro J, Yim EKF, Su R, et al. Adhesive hydrogels tailored with cellulose nanofibers and ferric ions for highly sensitive strain sensors. Chem Eng J 2022;450:138256.
[14] Verma R, Didwal PN, Hwang JY, Park CJ. Recent progress in electrolyte development and design strategies for next-generation potassium-ion batteries. Batteries Supercaps 2021;4(9):1428–50.
[15] Manarin E, Corsini F, Trano S, Fagiolari L, Amici J, Francia C, et al. Cardanol-derived epoxy resins as biobased gel polymer electrolytes for potassium-ion conduction. ACS Appl Polymer Mater 2022;4(5):3855–65.
[16] Trano S, Corsini F, Pascuzzi G, Giove E, Fagiolari L, Amici J, et al. Lignin as polymer electrolyte precursor for stable and sustainable potassium batteries. ChemSusChem 2022;15(12):1–9.
[17] Amici J, Torchio C, Versaci D, Dessantis D, Marchisio A, Caldera F, et al. Nanosponge-based composite gel polymer electrolyte for safer Li-O2 batteries. Polymers 2021;13(10):1625.
[18] Alidoost M, Mangini A, Caldera F, Anceschi A, Amici J, Versaci D, et al. Micro-mesoporous carbons from cyclodextrin nanosponges enabling high-capacity silicon anodes and sulfur cathodes for lithiated Si-S batteries. Chem-Eur J 2022;28(6):e202104201.
[19] Sadegh Ebrahimi M, Hashemi R, Etemadi E. In-plane energy absorption characteristics and mechanical properties of 3D printed novel hybrid cellular structures. J Mater Res Technol 2022;20:3616–32.
[20] Sun G, Huo X, Wang H, Hazell PJ, Li Q. On the structural parameters of honeycomb-core sandwich panels against low-velocity impact. Compos B Eng 2021;216:108881.
[21] Amir AL, Ishak MR, Yidris N, Zuhri MYM, Asyraf MRM. Advances of composite cross arms with incorporation of material core structures: manufacturability, recent progress and views. J Mater Res Technol 2021;13:1115–31.
[22] Gohar S, Hussain G, Ilyas M, Ali A. Performance of 3D printed topologically optimized novel auxetic structures under compressive loading: experimental and FE analyses. J Mater Res Technol 2021;15:394–408.
[23] Li B, Lu Z, Yan K, Lu S, Kong L, Xu P. Experimental study of a honeycomb energy-absorbing device for high-speed trains. Proc Inst Mech Eng - Part F J Rail Rapid Transit 2020;234(10):1170–83.
[24] Zhang Y, Yan L, Zhang W, Su P, Han B, Guo S. Metallic tube-reinforced aluminum honeycombs: compressive and bending performances. Compos B Eng 2019;171:192–203.
[25] Ingrole A, Aguirre TG, Fuller L, Donahue SW. Bioinspired energy absorbing material designs using additive manufacturing. J Mech Behav Biomed Mater 2021;119:104518.
[26] Ha NS, Lu G. A review of recent research on bio-inspired structures and materials for energy absorption applications. Compos B Eng 2020;181:107496.
[27] Lazarus BS, Velasco-Hogan A, Gómez-del Río T, Meyers MA, Jasiuk I. A review of impact resistant biological and bioinspired materials and structures. J Mater Res Technol 2020;9(6):15705–38.
[28] Nian Y, Wan S, Li M, Su Q. Crashworthiness design of self-similar graded honeycomb-filled composite circular structures. Construct Build Mater 2020;233:117344.
[29] Nian Y, Wan S, Li X, Su Q, Li M. How does bio-inspired graded honeycomb filler affect energy absorption characteristics? Thin-Walled Struct 2019;144:106269.
[30] Ghamarian A, Zarei HR, Abadi MT. Experimental and numerical crashworthiness investigation of empty and

foam-filled end-capped conical tubes. Thin-Walled Struct 2011;49(10):1312–9.
[31] Jones N. Energy-absorbing effectiveness factor. Int J Impact Eng 2010;37(6):754–65.
[32] Meidell A. Computer aided material selection for circular tubes designed to resist axial crushing. Thin-Walled Struct 2009;47(8–9):962–9.
[33] Yuen S, Nurick G. The energy-absorbing characteristics of tubular structures with geometric and material modifications: an overview. Appl Mech Rev 2008;61(2).
[34] Olabi A-G, Morris E, Hashmi M. Metallic tube type energy absorbers: a synopsis. Thin-Walled Struct 2007;45(7–8):706–26.
[35] Alghamdi A. Collapsible impact energy absorbers: an overview. Thin-Walled Struct 2001;39(2):189–213.
[36] Li S, Guo X, Liao J, Li Q, Sun G. Crushing analysis and design optimization for foam-filled aluminum/CFRP hybrid tube against transverse impact. Compos B Eng 2020;196:108029.
[37] Tarlochan F. Sandwich structures for energy absorption applications: a review. Materials 2021;14(16):4731.
[38] Tarlochan F, Samer F, Hamouda A, Ramesh S, Khalid K. Design of thin wall structures for energy absorption applications: enhancement of crashworthiness due to axial and oblique impact forces. Thin-Walled Struct 2013;71:7–17.
[40] Zhang J, Lu G, You Z. Large deformation and energy absorption of additively manufactured auxetic materials and structures: a review. Compos B Eng 2020;201:108340.
[41] Djamaluddin F, Abdullah S, Ariffin A, Nopiah Z. Optimization of foam-filled double circular tubes under axial and oblique impact loading conditions. Thin-Walled Struct 2015;87:1–11.
[42] Yusof NSB, Sapuan SM, Sultan MTH, Jawaid M, Maleque MA. Design and materials development of automotive crash box: a review. Ciência & Tecnologia dos Materiais 2017;29(3):129–44.
[43] Hussain NN, Regalla SP, Rao YVD. Comparative study of trigger configuration for enhancement of crashworthiness of automobile crash box subjected to axial impact loading. Procedia Eng 2017;173:1390–8.
[44] Dimas A, Dirgantara T, Gunawan L, Jusuf A, Putra IS. The effects of spot weld pitch to the axial crushing characteristics of top-hat crash box, applied mechanics and materials. Trans Tech Publ; 2014. p. 578–82.
[45] Saenz-Dominguez I, Tena I, Esnaola A, Sarrionandia M, Torre J, Aurrekoetxea J. Design and characterisation of cellular composite structures for automotive crash-boxes manufactured by out of die ultraviolet cured pultrusion. Compos B Eng 2019;160:217–24.
[46] Zukas JA, Nicholas T, Swift HF, Greszczuk LB, Curran DR, Malvern L. Impact dynamics. J Appl Mech 1983;50(3):702.
[47] Vincent JF, Bogatyreva OA, Bogatyrev NR, Bowyer A, Pahl A-K. Biomimetics: its practice and theory. J R Soc Interface 2006;3(9):471–82.
[48] Estrada S, Múnera JC, Hernández J, Arroyave M, Arola D, Ossa A. Bioinspired hierarchical impact tolerant materials. Bioinspiration Biomimetics 2020;15(4):046009.
[49] Jia Z, Yu Y, Hou S, Wang L. Biomimetic architected materials with improved dynamic performance. J Mech Phys Solid 2019;125:178–97.
[50] Xu Y. Hierarchical materials, Modern inorganic synthetic chemistry. Elsevier; 2017. p. 545–74.
[51] Zou M, Xu S, Wei C, Wang H, Liu Z. A bionic method for the crashworthiness design of thin-walled structures inspired by bamboo. Thin-Walled Struct 2016;101:222–30.
[52] Hu D, Wang Y, Song B, Dang L, Zhang Z. Energy-absorption characteristics of a bionic honeycomb tubular nested structure inspired by bamboo under axial crushing. Compos B Eng 2019;162:21–32.
[53] San Ha N, Lu G. A review of recent research on bio-inspired structures and materials for energy absorption applications. Compos B Eng 2020;181:107496.
[54] Tsang HH, Raza S. Impact energy absorption of bio-inspired tubular sections with structural hierarchy. Compos Struct 2018;195:199–210.
[55] Hao P, Du J. Mechanical properties of bio-mimetic energy-absorbing materials under impact loading. J Mater Sci 2018;53(5):3189–97.
[56] Raju K, Smith B, Tomblin J, Liew K, Guarddon J. Impact damage resistance and tolerance of honeycomb core sandwich panels. J Compos Mater 2008;42(4):385–412.
[57] Clark J, Jenson S, Schultz J, Hoffman J, Takak S, Ali M, et al. Study of impact properties of a fluid-filled honeycomb structure, ASME international mechanical engineering congress and exposition. American Society of Mechanical Engineers; 2013. V009T10A044.
[58] Ha NS, Lu G, Xiang X. Energy absorption of a bio-inspired honeycomb sandwich panel. J Mater Sci 2019;54(8):6286–300.
[59] Dear J, Lee H, Brown S. Impact damage processes in composite sheet and sandwich honeycomb materials. Int J Impact Eng 2005;32(1–4):130–54.
[60] Wang D, Chen D, Chen Z. Recent progress in 3D printing of bioinspired structures. Frontiers in Materials 2020;7:286.
[61] Gibson LJ. Cellular solids. MRS Bull 2003;28(4):270–4.
[62] Siddique SH, Hazell PJ, Wang H, Escobedo JP, Ameri AAH. Lessons from nature: 3D printed bio-inspired porous structures for impact energy absorption – a review. Addit Manuf 2022;58:103051.
[63] Wierzbicki T. Crushing analysis of metal honeycombs. Int J Impact Eng 1983;1(2):157–74.
[65] Zhang Q, Yang X, Li P, Huang G, Feng S, Shen C, et al. Bioinspired engineering of honeycomb structure–Using nature to inspire human innovation. Prog Mater Sci 2015;74:332–400.
[66] Zhang X, Zhang H. Theoretical and numerical investigation on the crush resistance of rhombic and kagome honeycombs. Compos Struct 2013;96:143–52.
[67] Baroutaji A, Sajjia M, Olabi A-G. On the crashworthiness performance of thin-walled energy absorbers: recent advances and future developments. Thin-Walled Struct 2017;118:137–63.
[68] Thomas T, Tiwari G. Crushing behavior of honeycomb structure: a review. Int J Crashworthiness 2019;24(5):555–79.
[69] Bitzer T. Honeycomb technology: materials, design, manufacturing, applications and testing. Springer Science & Business; 1997. Media.
[70] Murcia Morales M, Gómez Ramos MJ, Parrilla Vázquez P, Díaz Galiano FJ, García Valverde M, Gámiz López V, et al. Distribution of chemical residues in the beehive compartments and their transfer to the honeybee brood. Sci Total Environ 2020;710:136288.
[71] Sun G, Huo X, Chen D, Li Q. Experimental and numerical study on honeycomb sandwich panels under bending and in-panel compression. Mater Des 2017;133:154–68.
[72] Asprone D, Auricchio F, Menna C, Morganti S, Prota A, Reali A. Statistical finite element analysis of the buckling behavior of honeycomb structures. Compos Struct 2013;105:240–55.
[73] Camata G, Shing PB. Static and fatigue load performance of a gfrp honeycomb bridge deck. Compos B Eng 2010;41(4):299–307.

[74] Khan MS, Abdul-Latif A, Koloor SSR, Petrů M, Tamin MN. Representative cell analysis for damage-based failure model of polymer hexagonal honeycomb structure under the out-of-plane loadings. Polymers 2021;13(1):52.

[75] Papka SD, Kyriakides S. In-plane biaxial crushing of honeycombs—: Part II: Analysis. Int J Solid Struct 1999;36(29):4397–423.

[76] Lira C, Scarpa F. Transverse shear stiffness of thickness gradient honeycombs. Compos Sci Technol 2010;70(6):930–6.

[77] Xu F, Zhang X, Zhang H. A review on functionally graded structures and materials for energy absorption. Eng Struct 2018;171:309–25.

[78] Ruan D, Lu G, Wang B, Yu TX. In-plane dynamic crushing of honeycombs—a finite element study. Int J Impact Eng 2003;28(2):161–82.

[79] Shen CJ, Lu G, Yu TX. Dynamic behavior of graded honeycombs – a finite element study. Compos Struct 2013;98:282–93.

[80] Bates SRG, Farrow IR, Trask RS. Compressive behaviour of 3D printed thermoplastic polyurethane honeycombs with graded densities. Mater Des 2019;162:130–42.

[81] Ali M, Qamhiyah A, Flugrad D, Shakoor M. Theoretical and finite element study of a compact energy absorber. Adv Eng Software 2008;39(2):95–106.

[82] Zhang X-c, An L-q, Ding H-m. Dynamic crushing behavior and energy absorption of honeycombs with density gradient. J Sandw Struct Mater 2013;16(2):125–47.

[83] Wu X, Su Y, Shi J. In-plane impact resistance enhancement with a graded cell-wall angle design for auxetic metamaterials. Compos Struct 2020;247:112451.

[84] Yang C, Vora HD, Chang Y. Behavior of auxetic structures under compression and impact forces. Smart Mater Struct 2018;27(2):025012.

[85] Wu H, Zhang X, Liu Y. In-plane crushing behavior of density graded cross-circular honeycombs with zero Poisson's ratio. Thin-Walled Struct 2020;151:106767.

[86] Hou Y, Tai YH, Lira C, Scarpa F, Yates JR, Gu B. The bending and failure of sandwich structures with auxetic gradient cellular cores. Compos Appl Sci Manuf 2013;49:119–31.

[87] Fan T, Zou G. Influences of defects on dynamic crushing properties of functionally graded honeycomb structures. J Sandw Struct Mater 2014;17(3):295–307.

[88] Hu L, You F, Yu T. Analyses on the dynamic strength of honeycombs under the y-directional crushing. Mater Des 2014;53:293–301.

[89] Yang X, Xi X, Pan Q, Liu H. In-plane dynamic crushing of a novel circular-celled honeycomb nested with petal-shaped mesostructure. Compos Struct 2019;226:111219.

[90] Fan T. Dynamic crushing behavior of functionally graded honeycomb structures with random defects. Int J Mater Res 2016;107(9):783–9.

[91] Zhang J, Wei H, Wang Z, Zhao L. Dynamic crushing of uniform and density graded cellular structures based on the circle arc model. Lat Am J Solid Struct 2015;12:1102–25.

[92] Ouyang S, Deng Z, Hou X. Stress concentration in octagonal honeycombs due to defects. Compos Struct 2018;204:814–21.

[93] Wang Z, Li Z, Zhou W, Hui D. On the influence of structural defects for honeycomb structure. Compos B Eng 2018;142:183–92.

[94] Chen DH, Ozaki S. Stress concentration due to defects in a honeycomb structure. Compos Struct 2009;89(1):52–9.

[95] Zhu G, Li S, Sun G, Li G, Li Q. On design of graded honeycomb filler and tubal wall thickness for multiple load cases. Thin-Walled Struct 2016;109:377–89.

[96] de Waal L, You Z. Graded origami honeycomb tube for energy absorption, international design engineering technical conferences and computers and information in engineering conference. American Society of Mechanical Engineers; 2019. V05BT07A040.

[97] Zhang X-C, Liu Y, Wang B, Zhang Z-M. Effects of defects on the in-plane dynamic crushing of metal honeycombs. Int J Mech Sci 2010;52(10):1290–8.

[98] Hariharan K, Kalaivani K, Balachandran G. Foil optimization in tailor welded blank of an automotive floor component. Mater Manuf Process 2012;27(9):936–42.

[99] Meyer A, Wietbrock B, Hirt G. Increasing of the drawing depth using tailor rolled blanks—numerical and experimental analysis. Int J Mach Tool Manufact 2008;48(5):522–31.

[100] Sun G, Xu F, Li G, Li Q. Crashing analysis and multiobjective optimization for thin-walled structures with functionally graded thickness. Int J Impact Eng 2014;64:62–74.

[101] Zhang D, Fei Q, Jiang D, Li Y. Numerical and analytical investigation on crushing of fractal-like honeycombs with self-similar hierarchy. Compos Struct 2018;192:289–99.

[102] Yin H, Huang X, Scarpa F, Wen G, Chen Y, Zhang C. In-plane crashworthiness of bio-inspired hierarchical honeycombs. Compos Struct 2018;192:516–27.

[103] Tao Y, Li W, Wei K, Duan S, Wen W, Chen L, et al. Mechanical properties and energy absorption of 3D printed square hierarchical honeycombs under in-plane axial compression. Compos B Eng 2019;176:107219.

[104] Wang Z-G, Shi C, Ding S-S, Liang X-F. Crashworthiness of innovative hexagonal honeycomb-like structures subjected to out-of-plane compression. J Cent S Univ 2020;27(2):621–8.

[105] Zhang Y, Chen T, Xu X, Hu Z. Out-of-plane mechanical behaviors of a side hierarchical honeycomb. Mech Mater 2020;140:103227.

[106] Yang X, Sun Y, Yang J, Pan Q. Out-of-plane crashworthiness analysis of bio-inspired aluminum honeycomb patterned with horseshoe mesostructure. Thin-Walled Struct 2018;125:1–11.

[107] He Q, Feng J, Zhou H. A numerical study on the in-plane dynamic crushing of self-similar hierarchical honeycombs. Mech Mater 2019;138:103151.

[108] He Q, Feng J, Chen Y, Zhou H. Mechanical properties of spider-web hierarchical honeycombs subjected to out-of-plane impact loading. J Sandw Struct Mater 2020;22(3):771–96.

[109] Fan H, Luo Y, Yang F, Li W. Approaching perfect energy absorption through structural hierarchy. Int J Eng Sci 2018;130:12–32.

[110] Yang X, Ma J, Sun Y, Yang J. Ripplecomb: a novel triangular tube reinforced corrugated honeycomb for energy absorption. Compos Struct 2018;202:988–99.

[111] Qiao J, Chen C. In-plane crushing of a hierarchical honeycomb. Int J Solid Struct 2016;85:57–66.

[112] Mousanezhad D, Ebrahimi H, Haghpanah B, Ghosh R, Ajdari A, Hamouda AMS, et al. Spiderweb honeycombs. Int J Solid Struct 2015;66:218–27.

[113] Sun G, Jiang H, Fang J, Li G, Li Q. Crashworthiness of vertex based hierarchical honeycombs in out-of-plane impact. Mater Des 2016;110:705–19.

[114] Wang Z, Li Z, Shi C, Zhou W. Mechanical performance of vertex-based hierarchical vs square thin-walled multi-cell structure. Thin-Walled Struct 2019;134:102–10.

[115] Tao Y, Li W, Cheng T, Wang Z, Chen L, Pei Y, et al. Out-of-plane dynamic crushing behavior of joint-based

hierarchical honeycombs. J Sandw Struct Mater 2020:1099636220909783.
[116] Chen Y, Li T, Jia Z, Scarpa F, Yao C-W, Wang L. 3D printed hierarchical honeycombs with shape integrity under large compressive deformations. Mater Des 2018;137:226–34.
[117] Zhang Y, He N, Song X, Chen T, Chen H. On impacting mechanical behaviors of side fractal structures. Thin-Walled Struct 2020;146:106490.
[118] Xu X, Zhang Y, Wang J, Jiang F, Wang CH. Crashworthiness design of novel hierarchical hexagonal columns. Compos Struct 2018;194:36–48.
[119] Sun G, Chen D, Wang H, Hazell PJ, Li Q. High-velocity impact behaviour of aluminium honeycomb sandwich panels with different structural configurations. Int J Impact Eng 2018;122:119–36.
[120] Zhang W, Yin S, Yu TX, Xu J. Crushing resistance and energy absorption of pomelo peel inspired hierarchical honeycomb. Int J Impact Eng 2019;125:163–72.
[121] Chen J, Zhang X, Okabe Y, Saito K, Guo Z, Pan L. The deformation mode and strengthening mechanism of compression in the beetle elytron plate. Mater Des 2017;131:481–6.
[122] Cui J, Jiang M, Nicola M, Masic A, Qin Z. Multiscale understanding in fracture resistance of bamboo skin. Extreme Mechanics Letters 2021;49:101480.
[123] Zhang W, Yu TX, Xu J. Uncover the underlying mechanisms of topology and structural hierarchy in energy absorption performances of bamboo-inspired tubular honeycomb. Extreme Mechanics Letters 2022;52:101640.
[124] Ufodike CO, Wang H, Ahmed MF, Dolzyk G, Jung S. Design and modeling of bamboo biomorphic structure for in-plane energy absorption improvement. Mater Des 2021;205:109736.
[125] Osorio L, Trujillo E, Van Vuure A-W, Lens F, Ivens J, Verpoest I. The relationship between the bamboo fibre microstructure and mechanical properties. In: Proceedings 14th European conference on composite materials (on cd-rom). Budapest University of Technology and Economics. Department of Polymer; 2010.
[126] Seidel R, Thielen M, Schmitt C, Bührig-Polaczek A, Fleck C, Speck T. Fruit walls and nut shells as an inspiration for the design of bio-inspired impact resistant hierarchically structured materials. Design and Nature V 2010:421–30.
[127] Yang B, Chen W, Xin R, Zhou X, Tan D, Ding C, et al. Pomelo peel-inspired 3D-printed porous structure for efficient absorption of compressive strain energy. JBE 2022;19(2):448–57.
[128] Reddy SC. Ocular injuries by durian fruit. Int J Ophthalmol 2012;5(4):530.
[129] Ha NS, Lu G, Shu D, Yu TX. Mechanical properties and energy absorption characteristics of tropical fruit durian (Durio zibethinus). J Mech Behav Biomed Mater 2020;104:103603.
[130] Chen Q, Pugno NM. In-plane elastic buckling of hierarchical honeycomb materials. Eur J Mech Solid 2012;34:120–9.
[131] Fang J, Sun G, Qiu N, Pang T, Li S, Li Q. On hierarchical honeycombs under out-of-plane crushing. Int J Solid Struct 2018;135:1–13.
[132] Ha NS, Pham TM, Tran TT, Hao H, Lu G. Mechanical properties and energy absorption of bio-inspired hierarchical circular honeycomb. Compos B Eng 2022;236:109818.
[133] Gibson LJ. Biomechanics of cellular solids. J Biomech 2005;38(3):377–99.
[134] Ha NS, Le VT, Goo NS. Investigation of punch resistance of the Allomyrira dichtoloma beetle forewing. JBE 2018;15(1):57–68.
[135] Chen J, Zu Q, Wu G, Xie J, Tuo W. Review of beetle forewing structures and their biomimetic applications in China:(II) on the three-dimensional structure, modeling and imitation. Mater Sci Eng C 2015;55:620–33.
[136] Wang X, Qin R, Chen B. Laser-based additively manufactured bio-inspired crashworthy structure: energy absorption and collapse behaviour under static and dynamic loadings. Mater Des 2021;211:110128.
[137] Hao P, Du J. Energy absorption characteristics of bio-inspired honeycomb column thin-walled structure under impact loading. J Mech Behav Biomed Mater 2018;79:301–8.
[138] Xiang J, Du J, Li D, Scarpa F. Numerical analysis of the impact resistance in aluminum alloy bi-tubular thin-walled structures designs inspired by beetle elytra. J Mater Sci 2017;52(22):13247–60.
[139] Xiang J, Du J. Energy absorption characteristics of bio-inspired honeycomb structure under axial impact loading. Mater Sci Eng, A 2017;696:283–9.
[140] Zhang L, Bai Z, Bai F. Crashworthiness design for bio-inspired multi-cell tubes with quadrilateral, hexagonal and octagonal sections. Thin-Walled Struct 2018;122:42–51.
[141] Du J, Hao P. Investigation on microstructure of beetle elytra and energy absorption properties of bio-inspired honeycomb thin-walled structure under axial dynamic crushing. Nanomaterials 2018;8(9):667.
[142] Yu X, Pan L, Chen J, Zhang X, Wei P. Experimental and numerical study on the energy absorption abilities of trabecular–honeycomb biomimetic structures inspired by beetle elytra. J Mater Sci 2019;54(3):2193–204.
[143] Du J, Hao P, Liu M, Xue R, Li La. Energy absorbed ability and damage analysis for honeycomb sandwich material of bio-inspired micro aerial vehicle under low velocity impact. Proc IME C J Mech Eng Sci 2020:0954406220975427.
[144] Zhang Y, Wang J, Wang C, Zeng Y, Chen T. Crashworthiness of bionic fractal hierarchical structures. Mater Des 2018;158:147–59.
[145] May PR, Fuster JM, Haber J, Hirschman A. Woodpecker drilling behavior: an endorsement of the rotational theory of impact brain injury. Arch Neurol 1979;36(6):370–3.
[146] Lee N, Horstemeyer M, Rhee H, Nabors B, Liao J, Williams LN. Hierarchical multiscale structure–property relationships of the red-bellied woodpecker (Melanerpes carolinus) beak. J R Soc Interface 2014;11(96):20140274.
[147] Solak A, Temiztaş BA, Bolat B. Estimation of wavy honeycombs' compression performance via a machine learning algorithm. Lat Am J Solid Struct 2021;18.
[148] Patek SN, Korff W, Caldwell RL. Deadly strike mechanism of a mantis shrimp. Nature 2004;428(6985):819–20.
[149] Weaver JC, Milliron GW, Miserez A, Evans-Lutterodt K, Herrera S, Gallana I, et al. The stomatopod dactyl club: a formidable damage-tolerant biological hammer. Science 2012;336(6086):1275–80.
[150] Han Q, Qin H, Han Z, Zhang J, Niu S, Sun Y, et al. Study on mechanical properties of multi-structure dactyl-inspired sandwich honeycomb with basalt fiber. Compos Struct 2020;247:112467.
[151] Han Q, Qin H, Liu Z, Han Z, Zhang J, Niu S, et al. Experimental investigation on impact and bending properties of a novel dactyl-inspired sandwich honeycomb with carbon fiber. Construct Build Mater 2020;253:119161.
[152] Grunenfelder LK, Suksangpanya N, Salinas C, Milliron G, Yaraghi N, Herrera S, et al. Bio-inspired impact-resistant composites. Acta Biomater 2014;10(9):3997–4008.
[153] Kasapi MA, Gosline JM. Micromechanics of the equine hoof wall: optimizing crack control and material stiffness through modulation of the properties of keratin. J Exp Biol 1999;202(4):377–91.

[154] Huang W, Yaraghi NA, Yang W, Velazquez-Olivera A, Li Z, Ritchie RO, et al. A natural energy absorbent polymer composite: the equine hoof wall. Acta Biomater 2019;90:267–77.
[156] Kee Paik J, Thayamballi AK, Sung Kim G. The strength characteristics of aluminum honeycomb sandwich panels. Thin-Walled Struct 1999;35(3):205–31.
[157] Chai GB, Zhu S. A review of low-velocity impact on sandwich structures. Proc IME J Mater Des Appl 2011;225(4):207–30.
[158] Khan MS, Rahimian Koloor SS, Tamin MN. Effects of cell aspect ratio and relative density on deformation response and failure of honeycomb core structure. Mater Res Express 2020;7(1):015332.
[159] Tarlochan F, Hamouda A, Mahdi E, Sahari B. Composite sandwich structures for crashworthiness applications. Proc IME J Mater Des Appl 2007;221(2):121–30.
[160] Zhu F, Wang Z, Lu G, Nurick G. Some theoretical considerations on the dynamic response of sandwich structures under impulsive loading. Int J Impact Eng 2010;37(6):625–37.
[161] Qi C, Remennikov A, Pei L-Z, Yang S, Yu Z-H, Ngo TD. Impact and close-in blast response of auxetic honeycomb-cored sandwich panels: experimental tests and numerical simulations. Compos Struct 2017;180:161–78.
[162] Han B, Qin K, Yu B, Wang B, Zhang Q, Lu TJ. Honeycomb–corrugation hybrid as a novel sandwich core for significantly enhanced compressive performance. Mater Des 2016;93:271–82.
[163] Xiang X, Lu G, Ruan D, You Z, Zolghadr M. Large deformation of an arc-Miura structure under quasi-static load. Compos Struct 2017;182:209–22.
[164] Solak A, Temiztaş BA, Bolat B. Investigation of the effect of wavy honeycomb on the bending performance of the sandwich structure. J Sandw Struct Mater 2022;24(5):1905–19.
[165] Chen J, Dai G, Xu Y, Iwamoto M. Basic study of biomimetic composite materials in the forewings of beetles. Mater Sci Eng, A 2008;483–484:625–8.
[166] Cai Z-B, Li Z-Y, Ding Y, Zheng J, Liu J-H, Zhou Z-R. Preparation and impact resistance performance of bionic sandwich structure inspired from beetle forewing. Compos B Eng 2019;161:490–501.
[167] Bar-Sinai Y, Julien J-D, Sharon E, Armon S, Nakayama N, Adda-Bedia M, et al. Mechanical stress induces remodeling of vascular networks in growing leaves. PLoS Comput Biol 2016;12(4):e1004819.
[168] Sun Z, Shi S, Guo X, Hu X, Chen H. On compressive properties of composite sandwich structures with grid reinforced honeycomb core. Compos B Eng 2016;94:245–52.
[169] Cohal V. Spot Welding of honeycomb structures. In: IOP conference series: materials science and engineering. IOP Publishing; 2017, 012029.
[170] Shi C, Lu Z, Zhang K, Deng L, Wang C. Microstructure evolution and mechanical properties of γ-TiAl honeycomb structure fabricated by isothermal forging and pulse current assisted diffusion bonding. Intermetallics 2018;99:59–68.
[171] Huang X, Richards N. Activated diffusion brazing technology for manufacture of titanium honeycomb structures-a statistical study. Weld J 2004;83(3):73.
[172] Burton WS, Noor A. Structural analysis of the adhesive bond in a honeycomb core sandwich panel. Finite Elem Anal Des 1997;26(3):213–27.
[173] Wadley HNG. Multifunctional periodic cellular metals. Phil Trans Math Phys Eng Sci 2006;364(1838):31–68.
[174] Thompson MK, Moroni G, Vaneker T, Fadel G, Campbell RI, Gibson I, et al. Design for additive manufacturing: trends, opportunities, considerations, and constraints. CIRP annals 2016;65(2):737–60.
[175] Velasco-Hogan A, Xu J, Meyers MA. Additive manufacturing as a method to design and optimize bioinspired structures. Adv Mater 2018;30(52):1800940.
[176] Ahamed MK, Wang H, Hazell PJ. From biology to biomimicry: using nature to build better structures–A review. Construct Build Mater 2022;320:126195.
[177] Du Plessis A, Broeckhoven C, Yadroitsava I, Yadroitsev I, Hands CH, Kunju R, et al. Beautiful and functional: a review of biomimetic design in additive manufacturing. Addit Manuf 2019;27:408–27.
[178] Studart AR. Additive manufacturing of biologically-inspired materials. Chem Soc Rev 2016;45(2):359–76.
[179] Mohamed OA, Masood SH, Bhowmik JL. Optimization of fused deposition modeling process parameters: a review of current research and future prospects. Advances in manufacturing 2015;3(1):42–53.
[180] Hsiang Loh G, Pei E, Gonzalez-Gutierrez J, Monzón M. An overview of material extrusion troubleshooting. Appl Sci 2020;10(14):4776.
[181] Wang B, Zhou B, Zhang X. A high toughness and light weight armor structure bioinspired design based on a bovine hoof wall. Mater Lett 2020;264:127296.
[182] Sood AK, Ohdar RK, Mahapatra SS. Parametric appraisal of mechanical property of fused deposition modelling processed parts. Mater Des 2010;31(1):287–95.
[183] Mueller J, Courty D, Spielhofer M, Spolenak R, Shea K. Mechanical properties of interfaces in inkjet 3D printed single-and multi-material parts. 3D Print Addit Manuf 2017;4(4):193–9.
[184] Vaezi M, Drescher P, Seitz H. Beamless metal additive manufacturing. Materials 2020;13(4):922.
[185] Zhang X, Chen J, Okabe Y, Xie J, Zhang Z. Compression properties of metal beetle elytron plates and the elementary unit of the trabecular-honeycomb core structure. J Sandw Struct Mater 2019;21(6):2031–41.
[186] Benedetti M, Du Plessis A, Ritchie R, Dallago M, Razavi S, Berto F. Architected cellular materials: a review on their mechanical properties towards fatigue-tolerant design and fabrication. Mater Sci Eng R Rep 2021;144:100606.
[187] Wang X, Jiang M, Zhou Z, Gou J, Hui D. 3D printing of polymer matrix composites: a review and prospective. Compos B Eng 2017;110:442–58.
[188] Shen J, Lu G, Ruan D. Compressive behaviour of closed-cell aluminium foams at high strain rates. Compos B Eng 2010;41(8):678–85.
[189] Idris MI, Vodenitcharova T, Hoffman M. Mechanical behaviour and energy absorption of closed-cell aluminium foam panels in uniaxial compression. Mater Sci Eng, A 2009;517(1–2):37–45.

FURTHER READING

[39] Song J, Chen Y, Lu G. Light-weight thin-walled structures with patterned windows under axial crushing. Int J Mech Sci 2013;66:239–48.
[64] Chandrasekaran NK, Arunachalam V. State-of-the-art review on honeycomb sandwich composite structures with an emphasis on filler materials. Polym Compos 2021;42(10):5011–20.
[155] Fan J, Zhang L, Wei S, Zhang Z, Choi S-K, Song B, et al. A review of additive manufacturing of metamaterials and developing trends. Mater Today 2021;50:303–28.

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