PAPER • **OPEN ACCESS**

Literature review on thin-walled and cellular structure designs for energy absorption

To cite this article: T Dabasa *et al* 2023 *IOP Conf. Ser.: Mater. Sci. Eng.* **1294** 012046

Literature review on thin-walled and cellular structure designs for energy absorption

T Dabasa[1*], H G Lemu[2] and Y Regassa[1]

[1] Dept. of Mechanical Engineering, Addis Ababa Science and Technology University, Addis Ababa, Ethiopia
[2] Faculty of Science and Technology, University of Stavanger, N-4036 Stavanger, Norway

* Correspondence: tamana.dabasa@aastustudent.edu.et

Abstract. Bio-inspired structure is a topic of immense interest to researchers worldwide. In order to maximize energy absorption through biomimetic structures, this article presents bio-inspired structure particularly, thin walled and cellular structures thorough analysis of the interactions between experimental research and Finite Element Analysis (FEA) simulations. The study compiles the prior research on experimental investigations of thin-walled and cellular biomimetic structures in order to understand the significance of biomimetic structural energy absorption. These inventive works of nature serve as inspiration for these designs, which provide engineering solutions that excel in impact resistance and energy dissipation abilities. The study further highlights the mutual advantages of combining experimental research with FEA models, which enable a deeper understanding of the impact response and energy absorption mechanisms inherent in biomimetic structures, by exploring into recent developments in material science and design methodologies. The article emphasizes how important validations are in bringing experimental results in line with FEA predictions. Furthermore, the practical applications demonstrated in fields like aircraft engineering, automotive safety, and protections can serve as excellent examples of the paradigm-shifting potential of this method for boosting impact protection. This review proposes novel research avenues aimed at fully harnessing the potential of biomimetic architectures to enhance energy absorption, all while acknowledging and addressing the associated challenges.

Keywords: Biomimetic structures, Energy absorption, Thin-walled structure, cellular structures

1. Introduction

The ability of a structure to absorb and dissipate energy when subjected to an impact or external force is referred to as energy absorption. A system called the energy absorber transforms kinetic energy into another kind of energy [1]. Energy absorption must be taken into consideration during the engineering design process to reduce impact forces, increase structural safety, prevent collapses, protect equipment and products, and improve resilience, due to various structural elements found in biomimetic designs. Whether the design is inspired by plants, insects, or animals, it has consistently addressed one or more issues related to product/component optimization [2]. Modern scientists and engineers seek nature for optimal, economically viable, and long-term solutions.

Due to their extreme lightness and exceptional energy absorption capabilities, high energy-absorbing thin walled and cellular structure biomimetic designs are in high demand across a variety of technical sectors, including automobiles [3], aerospace [4], protective armours [5], biomedical fields [6] and civil engineering [7] due to their ultra-light and outstanding energy absorbing performance [8]. Consequently, several energy absorbers with different structures such as sandwich structures [9], plates [10], honeycomb [8], and foams [11] have been proposed in recent years. Various biological structures found in animals and plants could be used as inspiration to design novel structures that can sustain impacts generated during collision, exhibit excellent energy absorption capabilities and inspire the design of new energy absorbers. Further, a variety of materials have been used to manufacture bio-inspired structures, including ceramic, polymeric, metallic and fiber-reinforced composites and concrete [12]. It has always been possible for bio-inspired designs, whether they are based on plants or animals, to address one or more product/component optimization challenges [2].

Nowadays, the search for nature-inspired biomimetic is focused to develop best performing, most sustainable solutions. Two key methods are used to understand the performance of the solutions, particularly to investigate the mechanical properties and energy absorption of biomimetic structures: (1) experimental methods such as Drop-weight impact test [13], quasi-static compression test [14] and (2) FEA based simulations utilizing ABAQUS [8], ANSYS [15], and LS-DYNA [16]. Schematic images of some of the biomimetics testing approaches are shown in Figure 1.

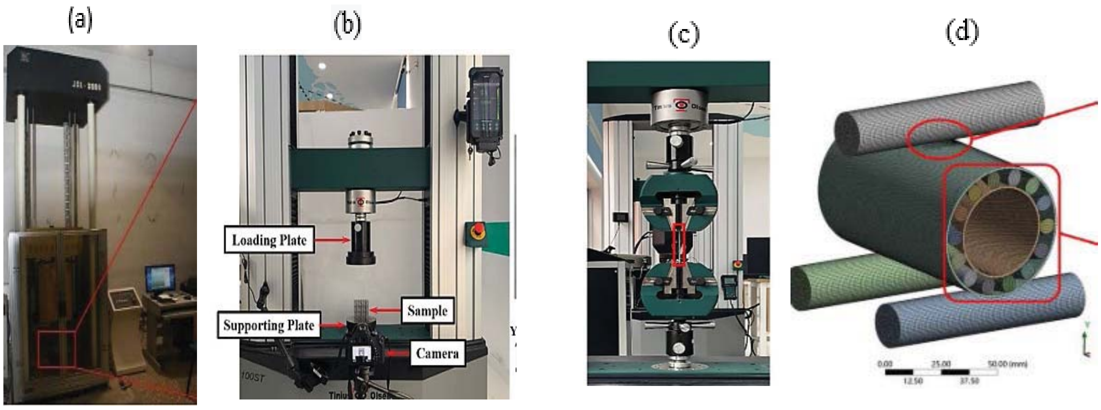


Figure 1. Schematic views of different testing techniques, (a) Drop-weight impact testing (b) Quasi-static compression test (c) Tensile test (d) Numerical simulation (FEA).

Observing the growing interest in use of biomimetic as nature-inspired design and analysis method, the objective of this article is to review recent research work on application of experimental and numerical research in this field. The review work is intended to lay the basis for continuing research in this direction.

2. Energy absorption criteria

Energy absorption (EA) quantifies the energy absorbed during compression and is calculated as the area under the compressive stress–strain curve, as depicted in Figure 2. Key parameters used for assessing energy absorption performance include EA, specific energy absorption (SEA), mean crush force (Pm), maximum crush force (Pmax), and crush load efficiency (CLE), which are crucial for evaluating crashworthiness [17].

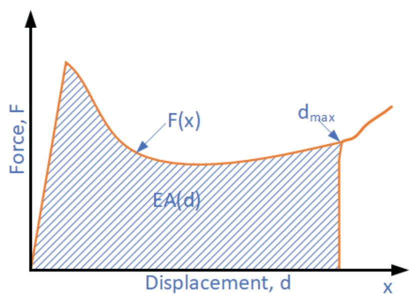


Figure 2. Force-displacement relationship of energy absorbers, where the absorbed energy is represented by the shaded area under the curve.

Energy absorption reflects the structure's capacity to absorb total impact energy, determined by integrating the crush force displacement curve (Equation (1)), while SEA measures the absorbed energy per unit mass of the structure (Equation (2)). As can be observed from the equation, higher SEA values correspond to higher elastic energy per unit mass, which indicates better energy-absorption capabilities. Pm (mean crushing force), on the other hand signifies the average compression force resisted during the total plastic deformation process and is calculated using Equation (3). In addition to calculation of the amount of energy absorbed, the uniformity of the crush-force displacement is also important to measure the crash load efficiency (CLE). This parameter is defined as the ratio of P_m to P_{max} (i.e., peak crushing force PCF), where P_{max} is the maximum of F(x), as given by Equation (4).

$$EA = \int_0^x F(x)dx \tag{1}$$

$$SEA = \frac{EA}{m} \tag{2}$$

$$P_m = \frac{EA}{x} \tag{3}$$

$$CLE = \frac{P_m}{P_{max}} \tag{4}$$

Where F(x) represents the instantaneous crush force at the effective crushing distance x and m is the total mass of the structure.

3. Methods studying biomimetic structure for energy absorption

The mechanical behaviour and energy absorption of biomimetic structures are explored using two essential techniques, which are highlighted in this section. It combines numerical simulations and experimental research (Figure 3) from previous studies to provide understanding of anticipated results.

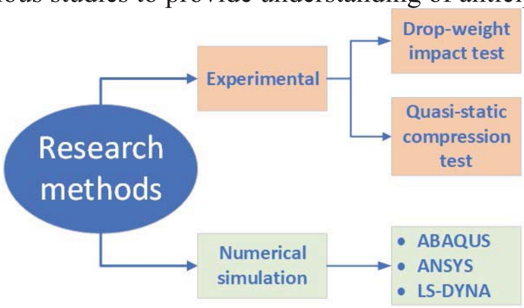


Figure 3. Methods for biomimetic structure for energy absorption.

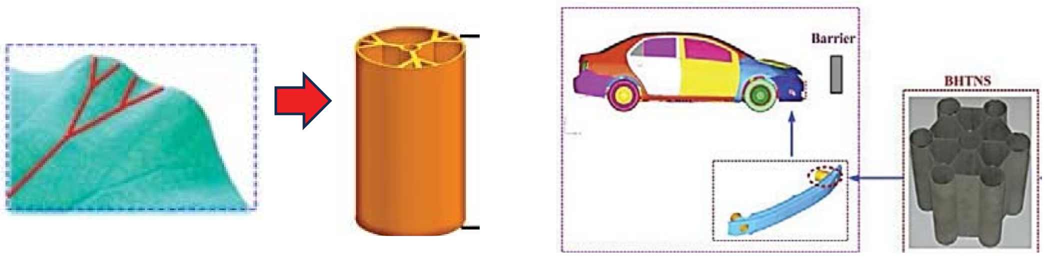
3.1 Experimental analysis of biomimetic structures

Experimental analysis of biomimetic structures involves conducting physical tests and measurements on structures that are inspired by biological systems. These tests aim to evaluate the mechanical properties, performance, and energy absorption behaviour of these biomimetic structures under various conditions. The goal of experimental analysis is to gain insights into how these structures emulate natural systems and to assess their potential applications in engineering design and other fields. Bio-inspired structures for energy absorption experimental attempts made are particularly investigated for thin-walled structures and cellular structures.

3.1.1 Biomimetic thin-walled structure: Thin-walled structures have gained substantial attraction in industries such as automobile and aviation due to their lightweight, cost-effective, and high energy absorption properties [17]. Extensive research has focused on investigating the deformation modes [8] and energy absorption [18] of these structures. This exploration combines numerical simulations [19] and experimental studies like drop and quasi static test [20, 21]. Most common thin-walled structures are circular tubes like multi-cell tubes, multi-corner tubes, corrugated, and tapered tubes are thin-walled structure commonly used for energy absorption due to their high rigidity, strength, affordability, variety, and ease of manufacture [22].

Researchers have contributed significantly to the design evolution of energy-absorbing components within thin-walled tubes. Various strategies including structural modifications and diverse cross-sectional configurations such as circular, square [23], hexagonal [24] and non-convex multi-corner structures have been employed. Furthermore, hybrid structures [25], gradient thickness variations [21], and tapered tubes [22], as well as corrugated tubes [26] have been thoroughly examined. From previous studies, cross sectional configuration has a great effect on biomimetic structure. The impact performances of the multi-corner tubes with cross section of star-shaped were studied based on experimentally dynamic test and their numerical simulations were validated through impact tests on Aluminium ABAQUSS-tube samples. Due to its distinctive deformation mode, the S-tube's specific energy absorption exceeded that of polygon tubes (P-tube) [27]. As indicated in Figure 4 (a) lotus leaf inspired were designed for novel biomimetic hierarchical thin-walled structure (BHTS) design that has various advantages over conventional approaches to creating energy absorption structures [28].

Building on past work [29], bionic crossbeam and box designs, inspired by bamboo and cattail plants, significantly enhanced crashworthiness under quasi-static tests. In Figure 4 (b), designs reduced overall weight and crush deformation by 33.33% and 44.44%, respectively. Research into round and square cross sections of Al alloy thin-walled tubes [23] underscored the round section's superior energy absorption under quasi-static axial loading. Frusta and tapered tubes with varied cross-sectional forms have been extensively studied as energy absorbers due to their superior characteristics compared to circular tubes [22]. A novel thin-walled multi-cell tubular structure with a modified face-cantered cubic (MFCS) cross-section using experimental and numerical simulations in ABAQUS/Explicit 2020 software under quasi static were utilized. These studies showcased enhanced energy absorption, efficiency, and stable deformation [8]. A study in [30] investigated bionic tubes through drop weight tests, introducing three new tube types inspired by bamboo cross-sections. Notably, 8 out of 14 bionic specimens displayed greater SEA than cylindrical tubes, highlighting the efficacy of bionic design in innovations like bio-inspired aluminium honeycombs.



(a) (b)

Figure 4. (a) biomimetic structures inspired by a lotus leaf (b) Crash box of the vehicle with BHTNS inspired by the bamboo structure.

In another study [31] bionic thin-walled energy absorption structures inspired by bamboo's characteristics underwent comprehensive performance analysis. The quasi-static study conducted included specific energy absorption, peak crushing force, and load-carrying capacity behaviour under varying conditions. Bamboo-inspired honeycomb tubular structure was manufactured using the wire-cut electrical-discharge machining (WEDM), and subjected to a drop-weight impact test at an impact velocity of up to 4.4 m/s. It was concluded that the maximum specific energy absorption of the structures was higher than those of traditional metallic honeycomb structures (35 J/g) [32].

Use of foam-filled bionic structures are other ways to improve energy absorption. Horsetail bio-inspired multi-cell tubes (HBMTs) with foam were the subject of a numerical research using LS-DYNA, as well as an experimental lateral impact test with a 15 m/s impact velocity [33]. The foam density and wall thickness of the bio-inspired structure were discovered to have a substantial influence on their crashworthiness based on the examination of the novel design. When the bio-inspired construction was modelled with a 0.5 g/cm^3 foam density and a 3 mm tube thickness, the specific energy absorption was 1.6 kJ/kg. Another study [34] that was motivated by the cross-sections of bamboo and palms looked at the

IOP Conf. Series: Materials Science and Engineering 1294 (2023) 012046 doi:10.1088/1757-899X/1294/1/012046

energy absorption of multi-cell carbon fibre reinforced plastic (CFRP) and aluminium (Al) square tubes under quasi-static axial crushing.

Innovative configurations such as hybrid structures combining square and circular sections, were aimed to enhance energy absorption by introducing corners [25]. Bionic gradient thickness (BGT) tubes proposed for enhanced energy absorption underwent analysis, demonstrating improved deformation and energy absorption compared to uniform-thickness tubes [16]. Bamboo-inspired bionic design further enhanced energy absorption in thin-walled tubes attributed to gradient distribution of vascular bundles, nodes, and density. In order to determine the load-carrying and energy absorption capabilities of a thin-walled structure, researchers [35] studied it experimentally and numerically under quasi-static and dynamic loads. The structure was modelled after the biologic organism known as a balanus. The construction was deep drawn and consisted of an outer shell with a frusto-conical shape and an interior conical core with a hemispherical top. LS-DYNA was used to model the applied deep drawing process using a nonlinear finite element code. Additionally, it was demonstrated that the load supported by the balanus structure was larger than the total weight supported by the outer shell and inner core separately. At quasi-static strain rates, the mean force increase resulting from the interaction effect was around 5%, whereas at dynamic strain rates, it increased to nearly 26%.

3.1.2 Biomimetic cellular structure: Biomimetic cellular structures, inspired by nature, are designed for optimal energy absorption with applications in impact protection [36], automotive safety [19] and structural integrity [37]. Combining experiments and numerical methods, researchers are uncovering their performance potential. Cellular structures like foam-filled designs [19], lattice structure [38] and honeycomb [39] are most common structures used for energy absorption. Lattices have numerous superior qualities to foams and honeycombs, including light weight, high strength, energy absorption, and vibration reduction, all of which have received considerable attention [40]. Foam-filled straw structures have a great capacity for absorbing energy as shown in Figure 5. Based on two common straw constructions (Cornstalk and Reed), there are four different types of bio-inspired foam-filled structures as shown in Figure 5.

1) A bionic foam core with a central hole,
2) Four square holes,
3) Four taper holes, and
4) Two nodes.

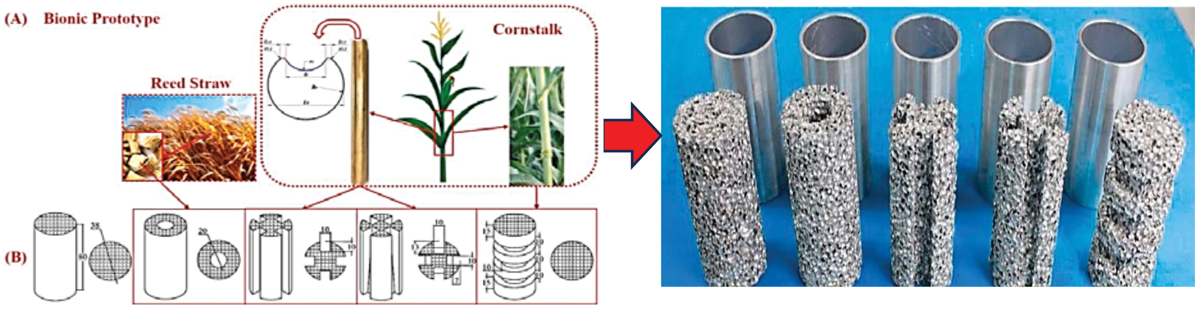


Figure 5. Bio-inspired aluminium foam-filled tubes

By using dynamic drop hammer and quasi-static compression, the energy absorption capacity and deformation mode of bionic structures were investigated [19]. According to the findings, 9 out of 12 bionic samples could absorb more energy than their matching fully filled counterparts. Exploring tortoiseshell-like composites [15], drop tests highlighted Bio-T composite's superior impact resistance compared to other structures (Bio-M, Bio-B, Bio N, HSP). Bio-T's arrangement at [0°/30°/0°] showed notably high load-bearing capacity prior to failure.

Uniquely shaped honeycomb with geometries influenced by natural shapes like the horseshoe, spiderweb, and pomelo peel are also used. Because they can survive high-stress impact situations, hooves have shown promising energy absorption properties and have similar porosity properties to human skin and have demonstrated promising energy absorption properties since they can withstand high-stress impact circumstances [41]. Horse-shaped aluminium honeycombs with different cross sections have been proposed based on triangular honeycomb, square honeycomb, hexagonal honeycomb and Kagome honeycomb to improve the energy absorption capacity and nonlinear explicit FEA code LS-DYNA was used [30]. In a work reported in [42] the unique microstructure of pomelo peel to create a novel hierarchical honeycomb structure was utilized. Spider-web hierarchy mimicking the porous honeycomb structure, crushing process was numerically simulated by LS-DYNA using a 400 kg impactor and a prescribed velocity of 15 m/s. The base material of the honeycomb was aluminium alloy 6060 T4.

Researchers [43] Hierarchical honeycombs are investigated to understand energy absorption characteristics compared to ordinary honeycombs in terms of their mechanical characteristics such as stiffness, and energy absorption and results reported that first-order spider-web hierarchical honeycomb's SEA increased by 62.1%, whereas second-order spider-web hierarchical honeycomb's SEA increased by 82.4%.

As shown in Figure 6 (a) researchers studied 3D printed cellular structures (spiral and honeycomb) using fused deposition modelling (FDM) technique with ABS plus material under compression for both experiential and numerical (ABAQUS), where crash tests showed spiral designs outperformed honeycomb in energy absorption [44]. Expanding on previous work, [45] developed shape-memory continuous fiber reinforced composite honeycomb structures (CFRCHSs) using fused filament fabrication (FFF) technique. The study highlighted the significant impact of honeycomb parameters to enhance compression behavior and energy absorption in 3D printed CFRCHSs.

Lattice structures are very good at absorbing energy [46] which indicated in Figure 6 (b). Lattice structure containing cubic cells, diamond cells, and re-entrant cells [47] conducted quasi-static test analysis, in which they investigated the failure process and stress-strain response of lattice structures as well as their dynamic load deformation behaviour. The lattice constructions clearly differed in their deformation behavior and energy absorption effect when subjected to low-speed and high-speed impact conditions.

Researchers in [46] looked at the degree to which uniform and graded lattice structures may absorb energy. According to the findings, the graded lattice structure absorbed 3.2 ± 0.1 MJ/m^3 of cumulative energy, while the uniform lattice structure absorbed 2.6 ± 0.2 MJ/m^3. For energy absorption, thin-walled structures filled or coated with various materials are being investigated [48]. The researchers developed novel hybrid structures thin-walled tubes filled with periodic lattice materials to increase energy absorption. As seen in Figure 6 (b), these hybrids showed a remarkable 115% improvement in impact energy absorption compared to the total of their individual components.

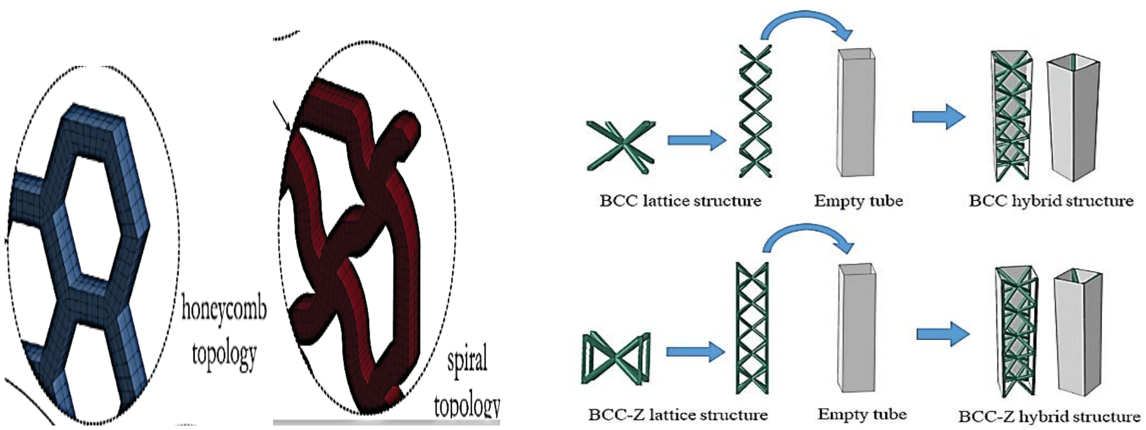


Figure 6. (a) Honeycomb and spiral structures (b)compressive behaviour of BCC and BCC-Z lattice.

IOP Conf. Series: Materials Science and Engineering 1294 (2023) 012046 doi:10.1088/1757-899X/1294/1/012046

3.2 Finite element modelling

The Finite Element Method (FEM) is vital in mechanical and structural engineering. Particularly, nonlinear FEM is valuable for large deformation plasticity problems, provides precise results compared to traditional methods. In various industries, FEA streamlines energy-absorbing structure design by replacing costly testing. These structures often collapse intricately under axial or multi-axial loads, challenging conventional analysis methods. Figure 7 illustrates an example of finite element model under impact testing which play a pivotal role in studying energy-absorbing structures [11].

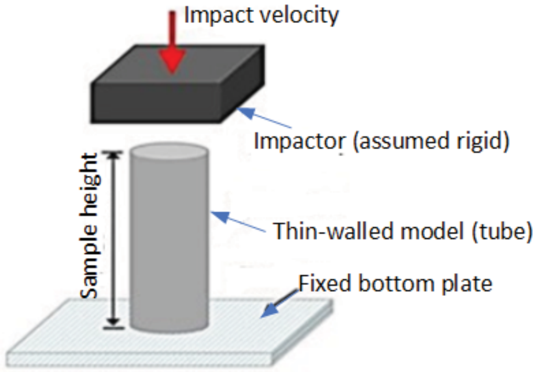


Figure 7. Finite element model under impact testing.

For meshing structures prior to simulations, choosing the right element size is essential to ensure accurate deformation and energy absorption analyses [17]. To visualize and mesh complex geometries, FEA tools such as Hypermesh, LS-Dyna utilising LS-Prepost file, and HyperView are helpful [16]. Lattice structures work best with the shrink wrap technique in Hypermesh [49]. Software like ABAQUS [50-52], ANSYS [6], and LS-DYNA [25,52] along with geometric models from SolidWorks and Catia meshed in HyperMesh [51] are used in FE models to imitate the behaviors of biomimetic structures. Quasi-static, dynamic, and impact simulations are all included in FEA, enabling thorough investigation of geometric parameters [18]. This includes analyzing PLA honeycombs with LS-DYNA, analyzing BHTS mechanical characteristics in ANSYS, and researching geometric parameter effects in ABAQUS. The paper evaluates 3D printed PLA honeycomb structures for sacrificial cladding solutions using experimental tests and LS-DYNA simulations. With a mesh size of 0.25 mm and second-order tetrahedral elements, Hypermesh uses the shrink wrap approach for meshing [49].

Quasi-static compression studies on selective laser melting (SLM)-printed specimens prepared in SolidWorks and simulated in ABAQUS were conducted on geometric parameter effects on energy absorption in HCFCC lattice structures [38]. The SEA of bio-inspired multi-cell conical tubes was observed to be higher than that of conventional designs, with a SEA of 46.2 kJ/kg, which is 1.3 and 1.8 times higher than that of conventional four-cell conical tubes, respectively [2]. The following is a representation of how the full finite element modelling of the simulation of biomimetic structures was evaluated, which were particularly used for simplicity of understanding.

3.2.1 Impact analysis: Nowadays, physical testing is becoming unnecessary because numerical simulations, such as LS-Dyna, ABAQUS, and ANSYS, can anticipate material and structure behavior under dynamic stresses precisely. The SEA of thin-walled constructions under dynamic axial loading in ABAQUS/Explicit with 4-node shell elements was observed to be 40% higher than that of P-tube [32]. ABAQUS/Explicit successfully simulates the energy absorption of bionic honeycomb tubular nested structures and showed good agreement with drop-weight experiment data. The development of nacre-inspired composite materials using impact testing and LS-DYNA computational modelling successfully prevents projectile perforation. Experimental impact tests and ABAQUS/Explicit simulations were used to examine the dynamic behaviour of thin-walled star-shaped cross-section tubes. When compared to square and circular multi-cell structures, hybrid structures can absorb up to 70.13% more energy, according to LS-DYNA numerical simulations

IOP Conf. Series: Materials Science and Engineering 1294 (2023) 012046 doi:10.1088/1757-899X/1294/1/012046

[25]. The finite-element model of BHTNS was established using ABAQUS/Explicit to simulate the drop-weight experiment (Figure 8).

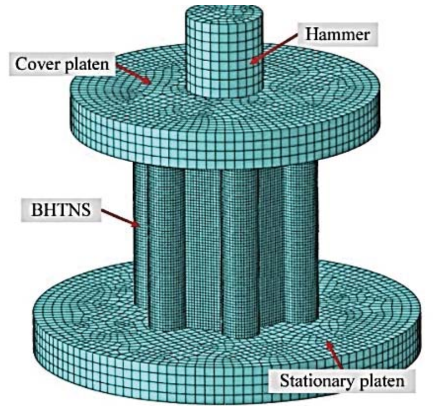


Figure 8. Finite modeling based on initial drop-weight experimental setups.

Aluminum alloy bio-inspired structures outperformed conventional honeycombs in terms of energy absorption. A 500 kg load and 10 m/s speed LS-DYNA investigation demonstrated their improved specific energy absorption [52]. Additionally, the ballistic impact resistance of bio-inspired composite scales and scale-like protective systems was evaluated numerically using LS-DYNA, with a focus on penetration resistance [53]. Using optimized hexagonal unit cell dimensions and density, ultralight bamboo-like structures with certain attributes were assessed using drop testing and Ansys simulations [15]. Energy absorption of lattice structures was shown to vary experimentally and numerically (using ABAQUS), with BLS A-6-0.75 and BLS B-6-0.2.5 showing slightly higher EA [48].

Researchers examined the mechanical durability and energy absorption of a bio-inspired honeycomb anti-collision pier using ABAQUS, selecting a central triangular section for enhanced performance [7]. Aluminum honeycombs with a horseshoe design that were inspired by nature were examined in LS-DYNA, and the results showed a considerable advantage in energy absorption, with a 63.9% increase in specific energy absorption [30]. A design inspired by trabecular bone demonstrated a 29% peak reduction and a 69% increase in energy absorption through successive buckling and collapse mechanisms. Using drop-hammer testing and Ansys simulations, a lightweight structure design inspired by the rostrum was optimized, yielding much greater total and specific energy absorption.

3.2.2 Deformation analysis: Numerical simulations via FEA predict material and structural deformation under various loads with quasi-static compression. Hybrid structures with external circle sections show improved deformation modes compared to inner circle sections [25]. Deformation and energy absorption analysis of bionic gradient thickness (BGT) tubes conducted in Ls-Dyna. Bionic circular tube (BCT) outperforms uniform-thickness circular tube (CT) in deformation and energy absorption, verified through quasi-static experiments [16]. LS-DYNA used to analyse horseshoe-shaped honeycombs, demonstrating improved plateau force and higher specific energy absorption, despite increased initial peak force [30]. Abaqus CAE 2017 simulations employed to study lattice structures' deformation and failure modes, revealing stress concentration sites [49].

Compression experiments are performed using bio-inspired energy-absorbing materials created utilising additive manufacturing with Beetle electron-DSM Somos 14120 resin. With a 15% greater compressive strength, 63% more deformation, and a staggering 115% increase in energy absorption, BEP outperforms HP. HP has an energy absorption of 154.80J and a specific energy absorption of 9.16 x 103 J/kg [54]. The geometrical characteristics are very important in the deformation mode. Conical corrugation tube (CCT), a unique tubular corrugated design resembling a coconut tree profile, was used to maximize energy absorption and reduce the initial peak crushing force. When compared to its circular straight tube and tapered tube equivalents, the CCT's initial peak force was significantly lower [55].

4. Optimization strategies for biomimetic energy absorption

Optimization strategies for energy absorption depend on problem complexity and design variables. Optimization objectives of biomimetic structure is based on specific energy absorption and peak crushing force that should be optimum solution [50].Common approaches include multi-objective optimisation with surrogate models for hybrid multi-cell structures [10],using Non-dominated Sorting Genetic Algorithm II (NSGA-II) for ship fender design to maximise SEA and minimise CFE Optimizing bionic structures inspired by bamboo with rate-dependent material models was implemented using Non-Sorting Genetic Algorithm 2 (NSGA2) in which 17% increase in energy absorption capacity was achieved [17]. Researchers in [17] investigated optimizing bionic tubes with different rib types to improve SEA. Using (NSGA-2), they determined the best-performing rib design, finding that the simple I-shape rib type P1 with 20 ribs yielded the highest energy absorption.

Improved crash performance and deformation mode of foam-filled ship fenders under quasi-static and dynamic stresses were the goals of [56]. Through simulation, six distinct fender models were evaluated. The examination criteria included crashworthiness factors including Specific Energy Absorption (SEA) and Crushing Force Efficiency (CFE). Finite element analysis was used to estimate crash responses and compare them to reference and experimental data. Height, foam density, thickness, and material were the four design parameters that were optimized. Non-dominated Sorting Genetic Algorithm II was used to increase SEA and decrease CFE. The Model 5 performed the best, showcasing its ability to replace traditional fender designs. Researchers [16] improved the BCT's (Bionic Composite Tube) crashworthiness design. They used multi-objective optimisation while taking the effect of load angle uncertainty into consideration. Peak force (PF) minimization and specific energy absorption (SEA) maximization were the two objectives. In comparison to the standard CT (Composite Tube), the ideal BCT showed a 9.3% increase in SEA and a 4% reduction in mass.

5. Validation of numerical models

Validating numerical models by comparing them with experimental or real-world data is crucial to ensure accurate representation of physical system behavior. Numerous studies have validated numerical results for both static and dynamic loading scenarios using experiments. For example, researcher in [32] studied axial crushing energy absorption of the BHTNS structure, with drop-weight impact experiments and computational models demonstrating reasonable agreement. LS-DYNA-based finite element modeling confirmed the impact performance of 3D-printed nacre-like composites, showing good alignment with experimental results. As shown in Figure 9, below comparison between experimental and numerical results were done on are:

a) Bionic gradient thickness (BGT) tubes [16],
b) Bionic honeycomb tubular nested structure (BHTNS) [52],
c) Hybrid tubes [25],
d) Bionic honeycomb thin-walled structure (BHTS) which filled the column in different ways inspired by the internal structure of the ladybeetle [53], and
e) Tube structure [57].

For the sake of comparison, the validation of numerical experiment with experimental work on different structures, reported in some research works are listed in Table 1. The error range obtained in these studies indicate that numerical research is well validated to be used instead of experimental research with significant cost benefits.

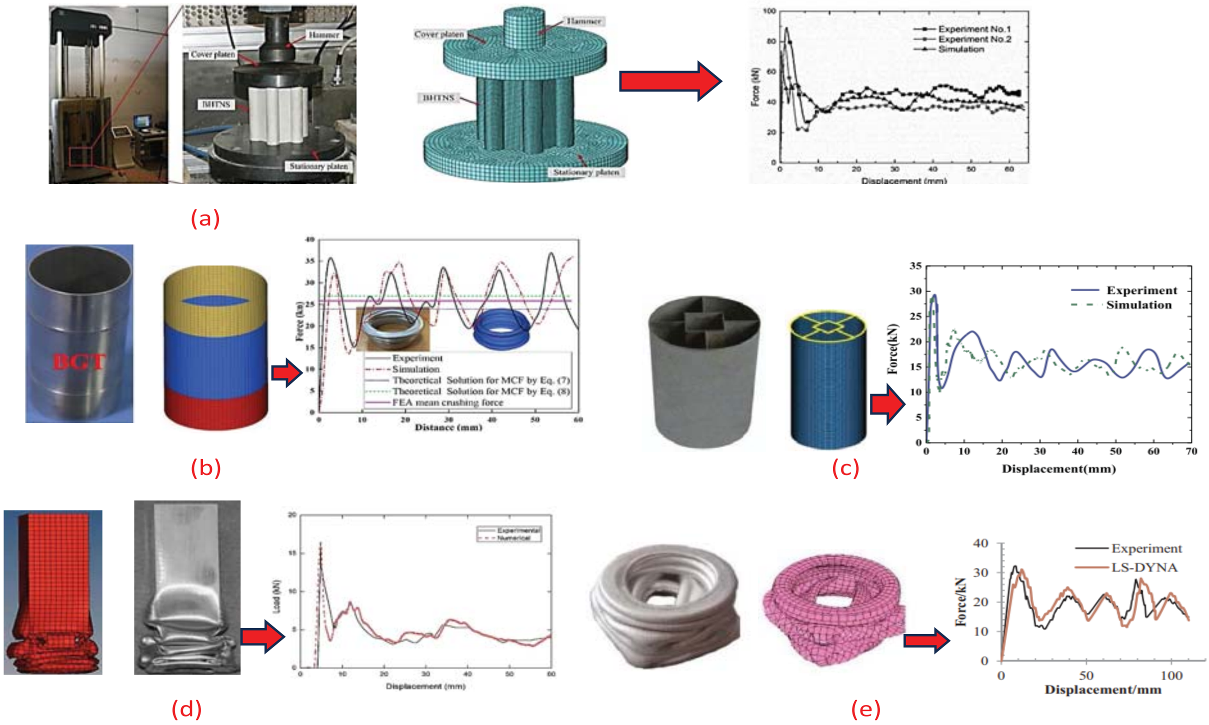


Figure 9. a comparison of experimental and numerical results for the following bionic structures: (a) bionic gradient thickness (BGT) tubes; (b) bionic honeycomb tubular nested structure (BHTNS); (c) hybrid tubes; (d) bionic honeycomb thin-walled structure (BHTS); (e) tube structure.

Table 1. Comparison of experimental and numerical results.

Structure	Methods	EA (J)	SEA (J/g)	PF(KN)	Ref.
BCT	Experiment	706.85	11.56	11.45	
	Numerical	673.82	11.38	10.81	[20]
	% error	4.9	1.61	5.92	
CS1	Experiment	-	9.74	29.65	[25]
	Numerical	-	9.29	30.14	
	% error	-	-4.62	1.65	
Foam filled fender	Experiment	133.569	-	21.9	[56]
	Numerical	133.637	-	22.4	
	% error	0.398	-	2.28	
Tube structure	Experiment	-	2.083	-	[57]
	Numerical	-	2.02	-	
	% error	-	0.903	-	
TPMS-CS structure	Experiment	669.97	-	66.07	[58]
	Numerical	669.97	-	65.92	
	% error	0.33	-	-1.34	

6. Conclusions

The finding of this study highlighted the significance of conducting impact and energy absorption analyses using FEA tools like ABAQUS, ANSYS, and LS-DYNA. Multi-objective optimisation approaches are recommended to handle trade-off problems and balance conflicting design objectives. Diverse biomimetic materials and structures are being actively investigated in research with the aim of enhancing energy absorption in a range of engineering applications. There are, nevertheless, considerable gaps in the literature. Although dynamic events frequently occur in biomimetic systems, the majority of recent study has been concentrated on quasi-static condition. To improve impact protection and crashworthiness, it is crucial to study the dynamic behaviour and energy absorption capabilities of biomimetic structures under high-energy situations.

Several key research gaps in the field of biomimetic structures and techniques of their analysis for energy absorption are noted for future work based on the literature review described in this article. Further research into alternative optimisation approaches is necessary despite the success of optimisation algorithms like genetic algorithms employing NSGA-II and particle swarm. Advanced optimisation techniques for the geometry and topology of structures, including their use in machine learning and artificial intelligence to find the best configurations suited to energy absorption needs, should also be investigated. Additionally, future study should also focus on the possible advantages of mixing several materials in one structure to maximise energy absorption, especially in figuring out how these materials interact with one another. In summary, this study highlights the promise of biomimetic structures in the field of energy absorption and impact prevention, while also identifying crucial areas for future research to address existing gaps and advance our understanding and capabilities in this field.

References

[1] Z. Zhao, X. Li, H. Jiang, X. Su, X. Zhang, and M. Zou 2023 Study on the mechanical properties and energy absorbing capability of polyurethane microcellular elastomers under different compressive strain rates, *Polymers*.,**15**(3), 778.

[2] A. Y. Patil, C. Hegde, G. Savanur, S. M. Kanakmood, and I. R. Fattah 2022 Biomimicking nature-inspired design structures-an experimental and simulation approach using additive manufacturing *Biomimetics,* **7**(4), 186.

[3] I. D. Wijegunawardana and W. R. de Mel 2021 Biomimetic designs for automobile engineering: A review, *IJAME*, **18**(3), 9029–9041,

[4] J. Yang, D. Gu, K. Lin, Y. Zhang, M. Guo, and L. Yuan 2022 Additive manufacturing frontiers laser additive manufacturing of bio-inspired metallic structures, *Chinese J. Mech. Eng. Addit. Manuf. Front.*, **1**(1), 100013.

[5] V. F. González-Albuixech, M. Rodríguez-Millán, T. Ito, J. A. Loya, and M. H. Miguélez 2018 Numerical analysis for design of bioinspired ceramic modular armors for ballistic protections, *Int. J. Damage Mech.,* vol. **28**(6) 815–837.

[6] Liang Meng, Hailong Liang, Hanchen Yu, Jingjing Yang, Fangzhi Li, Zemin Wang, and Xiaoyan Zeng 2019 The energy absorption and bearing capacity of light-weight bio-inspired structures produced by selective laser melting, *J. Mech. Behav. Biomed. Mater*., **93**, 170–182.

[7] B. H. A. Pier, J. Wei, Y. Wang, J. Wang, X. Yao, and D. Wang 2022 Mechanical strength and energy absorption optimization of biomimetic honeycomb anti-Collision Pier, *Buildings*, **12**(11), 1941.

[8] G. Sun, D. Chen, X. Huo, G. Zheng, and Q. Li 2018 Experimental and numerical studies on indentation and perforation characteristics of honeycomb sandwich panels, *Compos," Struct.,***184**, 110–124.

[9] M. Xu, L. Pan, J. Chen, X. Zhang, and X. Yu 2019 The flexural properties of end-trabecular beetle elytron plates and their flexural failure mechanism, *Journal of Materials Science,* **54**(1)

[10] P. Wang, F. Yang, H. Fan, and G. Lu 2023 Bio-inspired multi-cell tubular structures approaching ideal energy absorption performance, *Mater. Des.,* **225**, 111495.

[11] J. Du, P. Hao, and L. Li 2021 Finite element analysis of energy absorption characteristics for biomimetic thin-walled multi- cellular structure inspired by horsetails, *Mech. Adv. Mater. Struct.*, vol. **29**, 6982–6993.

[12] R. Shao, C. Wu, Y. Su, Z. Liu, J. Liu, and S. Xu 2019 Numerical analysis on impact response of ultra-high strength concrete protected with composite materials against steel ogivenosed projectile penetration, *Compos. Struct.,* **220**, 861–874.

[13] S. Wang, J. Wang, and K. Komvopoulos 2023 Mechanical behavior of bamboo-like structures under transversal compressive loading, *Biomimetics,* **8**(1), 103.

[14] S. H. Siddique, P. J. Hazell, G. G. Pereira, H. Wang, J. P. Escobedo, and A. A. H. Ameri 2023 On the mechanical behaviour of biomimetic cornstalk- inspired lightweight structures, *Biomimetics*, **8**(1), 92.
[15] J. Wang, D. Hu, Z. Zhang, B. Pei, R. Xu, and X. Wu 2022 Anti-impact performance of bionic tortoiseshell-like composites, *Compos. Struct.,* **303**, 116315.
[16] J. Song, S. Xu, J. Zhou, H. Huang, and M. Zou 2021 Thin-walled structures experiment and numerical simulation study on the bionic tubes with gradient thickness under oblique loading, *Thin-Walled Struct.,***163**(2), 107624.
[17] P. N. Panirani and J. Ghanbari 2022 Design and optimization of bio-inspired thin- walled structures for energy absorption applications, *Int. J. Crashworthiness*, **28**(1), 1-12.
[18] Ngoc San Ha 2020 Biomimetic structures and materials for energy absorption, *Euro. J. Appl. Eng. Sci*, **S**(3).
[19] J. Song, S. Xu, L. Xu, J. Zhou, and M. Zou 2020 Thin-walled structures experimental study on the crashworthiness of bio-inspired aluminum foam-filled tubes under axial compression loading, *Thin-Walled Struct.,***155**, 106937.
[20] X. Yu, L. Pan, J. Chen, X. Zhang, and P. Wei 2019 Experimental and numerical study on the energy absorption abilities of trabecular honeycomb biomimetic structures inspired by beetle elytra, *J. Mater. Sci.,* **54**(3), 2193–2204.
[21] H. B. Rebelo, D. Lecompte, C. Cismasiu, A. Jonet, B. Belkassem, and A. Maazoun, 2019 Experimental and numerical investigation on 3D printed PLA sacrificial honeycomb cladding, *Int. J. Impact Eng.,***131**, 162–173.
[22] N. S. Ha and G. Lu 2019 A review of recent research on bio-inspired structures and materials for energy absorption applications. *Composites Part B: Engineering*, **181**, 107496.
[23] A. Othman and A. E. Ismail 2018 Finite element modelling of AA6063T52 thin-walled tubes under quasi-static axial loading, *IOP Conf. Ser. Mater. Sci. Eng*., **342**(1).
[24] A. Ghazlan, T. Nguyen, T. Ngo, S. Linforth, and V. T. Le 2020 Performance of a 3D printed cellular structure inspired by bone, *Thin-Walled Struct.,***151**, 106713.
[25] T. Chen, Y. Zhang, J. Lin, and Y. Lu 2018 Thin-walled structures theoretical analysis and crashworthiness optimization of hybrid multi-cell structures, *Thin Walled Struct.,* **142**, 116–131.
[26] N. S. Ha and G. Lu 2020 Thin-walled corrugated structures: A review of crashworthiness designs and energy absorption characteristics, *Thin-Walled Struct.,***157**, 106995.
[27] W. Liu, Z. Lin, N. Wang, and X. Deng, 2016 Dynamic performances of thin-walled tubes with star-shaped cross section under axial impact, *Thin-Walled Struct.,* **100**, 25–37.
[28] L. Liu, L. Li, C. Guo, Y. Ge, Y. Chen, and L. Zhang 2023 The design of a biomimetic hierarchical thin-walled structure inspired by a lotus leaf and its mechanical performance analysis, *Materials*, **16**(11), 4116.
[29] T. Xu, N. Liu, Z. Yu, T. Xu, and M. Zou 2017 Crashworthiness design for bionic bumper structures inspired by cattail and bamboo, *Appl, Bionics Biomech*, **2017.**
[30] X. Yang, Y. Sun, J. Yang, and Q. Pan 2018 Thin-walled structures out-of-plane crashworthiness analysis of bio-inspired aluminum honeycomb patterned with horseshoe mesostructure, *Thin Walled Struct.*,**125,** 1–11.
[31] H. Zhang, Z. Huang, T. Li, C. Bao, and L. Zhang 2022 Multiple performance evaluation of bionic thin-walled structures with different cross sections considering complex conditions, J. *Environ. Public Health,* **2022.**
[32] D. Hu, Y. Wang, B. Song, L. Dang, and Z. Zhang 2018 Energy-absorption characteristics of a bionic honeycomb tubular nested structure inspired by bamboo under axial crushing, *Compos, Part B Eng,* **162**, 21–32.
[33] H. Yin, Y. Xiao, G. Wen, Q. Qing, X. Wu 2015 Crushing analysis and multi-objective optimization design for bionic thin-walled structure, *Mater. Des*, **87**, 825–834.
[34] E. Mahdi, D. Ochoa, A. Vaziri, and E. Eltai 2019 Energy absorption capability of date palm leaf fiber reinforced epoxy composites rectangular tubes, *Compos. Struct.,* **224**, 11100

[35] A. Tasdemirci, E. F. Akbulut, E. Guzel, F. Tuzgel, A. Yucesoy, and S. Sahin 2018 Thin-walled structures crushing behavior and energy absorption performance of a bio-inspired metallic structure: Experimental and numerical study, *Thin Walled Struct.,* **131**, 547–555.

[36] Shangqin Yuan, Chee Kai Chua, and Kun Zhou 2018 3D - printed mechanical metamaterials with high energy absorption*, Mater. Technol*, **4**(3).

[37] V. H. Carneiro, S. D. Rawson, H. Puga, J. Meireles, and P. J. Withers 2020 Additive manufacturing assisted investment casting: a low-cost method to fabricate periodic metallic cellular lattices, *Addit, Manuf.,* **33**, 10108.

[38] P. Wang, F. Yang, D. Ru, B. Zheng, and H. Fan 2021 Additive-manufactured hierarchical multi-circular lattice structures for energy absorption application, *Mater. Des.,* **210,** 110116.

[39] Y. Zhang, T. Liu, and W. Tizani, 2018 Experimental and numerical analysis of dynamic compressive response of nomex honeycombs, *Compos. Part B,* **148**, 27–39.

[40] Chen Pan, Yafeng Han and Jiping Lu 2020 Design and optimization of lattice structures: A review. *Appl. Sci*, **10**(18), 6374

[41] M. K. Islam, H. Wang, P. J. Hazell, M. A. Kader, and J. P. Escobedo 2022 Quasi-static response of horse hoof inspired biomimetic structures, *Mater, Today Proc*., **59**(1),1168–1173.

[42] W. Zhang, S. Yin, T. Yu, and J. Xu 2019 Crushing resistance and energy absorption of pomelo peel inspired hierarchical honeycomb, *Int, J. Impact Eng*, **125,** 163–172.

[43] W. Zhang, S. Yin, T. X. Yu, and X. J. C 2019 Crushing resistance and energy absorption of pomelo peel inspired hierarchical honeycomb, *Int. J. Impact Eng*.,**125**, 163–172.

[44] M. Kucewicz, P. Baranowski, M. Stankiewicz, M. Konarzewski, P. Płatek, and J. Małachowski 2019 Modelling and testing of 3D printed cellular structures under quasi-static and dynamic conditions, *Thin-Walled Struct.,* **145**, 1-15

[45] C. Zeng, L. Liu, W. Bian, J. Leng, and Y. Liu 2021 Compression behavior and energy absorption of 3D printed continuous fiber reinforced composite honeycomb structures with shape memory effects *Addit. Manuf.,* **38**(6), 10184.

[46] D. S. J. Al-Saedi, S. H. Masood, M. Faizan-Ur-Rab, A. Alomarah, and P. Ponnusamy, 2018 Mechanical properties and energy absorption capability of functionally graded F2BCC lattice fabricated by SLM, *Mater, Des*.,**144**, 32.

[47] Zuhal Ozdemir, Everth Hernandez-Nava, Andrew Tyas, James A. Warren, Stephen D. Fay, Russell Goodall, Iain Todd, and harm askes 2016 Energy absorption in lattice structures in dynamics: Experiments, *Int. J. Impact Eng*., **89**, 49–61

[48] E. Cetin and C. Baykasoğlu 2019 Energy absorption of thin-walled tubes enhanced by lattice structures, *Int. J. Mech. Sci.,* **157**, 471–484.

[49] Lucrezia Greco, Federica Buccino, Zhuo Xu, Laura Vergani, Filippo Berto, Mario Guagliano, Nima Razavi & Sara Bagherifard 2023 Design and analysis of energy absorbent bioinspired lattice structures, *J. Bionic Eng.,* **20**,1670–1686.

[50] K. Pajunen, P. Johanns, R. K. Pal, J. J. Rimoli, and C. Daraio 2019 Design and impact response of 3D-printable tensegrity-inspired structures, *Mater. Des.,* **182**, 107966.

[51] T. Van Le, A. Ghazlan, T. Ngo, and T. Nguyen 2020 Performance of a bio-mimetic 3D printed conch-lik structure under quasi-static loading, *Compos. Struct.,* **246**, 112433.

[52] D. Hu, Y. Wang, B. Song, L. Dang, and Z. Zhang 2019 Energy-absorption characteristics of a bionic honeycomb tubular nested structure inspired by bamboo under axial crushing, *Compos, Part B*, **162**, 21–32.

[53] P. Liu, D. Zhu, Y. Yao, J. Wang, and B. TQ 2016 Numerical simulation of ballistic impact behavior of bio-inspired scale-like protection system, *Mater. Des.,* **99**, 201–210.

[54] A. Ingrole, T. G. Aguirre, L. Fuller, and S. W. Donahue 2021 Materials Bioinspired energy absorbing material designs using additive manufacturing, *J. Mech. Behav. Biomed. Mater.,* **119**, 104518

[55] N. S. Ha, G. Lu, and X. Xiang 2018 International Journal of Mechanical Sciences High energy absorption efficiency of thin-walled conical corrugation tubes mimicking coconut tree configuration*, Int. J. Mech. Sci.,* **148**, 409–421

IOP Conf. Series: Materials Science and Engineering 1294 (2023) 012046 doi:10.1088/1757-899X/1294/1/012046

[56] F. Djamaluddin 2023 Finite element analysis and optimization of foam filled fender under quasi static and dynamic responses, *Front. Mech. Eng,* **9.**
[57] S. Pirmohammad and S. Esmaeili-Marzdashti 2019 Multi-objective crashworthiness optimization of square and octagonal bitubal structures including different hole shapes, *Thin-Walled Struct.,* **139**, 126–138.
[58] L. Liang, H. Zhu, D. Wei, Y. Wu, and W. Li, 2023 Energy absorption and multi-objective optimization of TPMS filled cylinder shell structures, *Electron. Res. Arch*, **31**(5), 2834-2854.