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Deformation behaviour, limitations in design, applications, and additive manufacturing of hierarchical honeycombs

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Abstract. Hierarchical honeycombs are particularly useful in aerospace industries because of their capability to overcome challenges related to bend-dominated behaviour. These structures are ideal for aeronautical applications because of their capacity to integrate lightweight design, good mechanical properties, and efficient load distribution. However, the efficacy under applied loads is influenced by the type of polygon cell typically introduced to the parent hollow structure. The current literature has gaps in knowledge regarding the highest order of hierarchy that can practically be achieved for hierarchical honeycombs with different cell shapes at the vertices or for the walls. This review paper documents work carried out on hierarchical honeycombs to examine their mechanical behaviour and how they can be efficiently designed. The first section of the paper highlights the deformation behaviour of hierarchical honeycombs in use today. The next section contains a discussion on the constraints in determining the order of hierarchy attainable for hierarchical honeycombs, particularly the geometric parameters. This is followed by a review of relevant applications for hierarchically built honeycomb parts in aerospace industries. The efficacy, as well as challenges related to using additive manufacturing in building hierarchical honeycombs, are then highlighted. Alternatives for future studies and advances in hierarchical honeycombs applied in the aerospace sector are addressed in the last section of the paper.

Keywords: Hierarchical honeycombs / polygon cells / mechanical properties / additive manufacturing

1 Introduction

Lightweight parts such as honeycombs (HCs) find use in the aerospace industries primarily due to the fact that they possess good mechanical properties and improved functionality [1–4]. Manufacturing HCs using lightweight materials, such as advanced composites and metal alloys, further supports the primary objective of reducing the weight of aircraft and spacecraft parts [1,3]. A lighter weight aircraft consumes lower volumes of gasoline, which in turn, improves the fuel efficiency as well as reducing the carbon footprint [1,5,6]. Aerospace industries are under pressure to reduce their impact with reference to gas emissions, and numerous studies [1,2,4,5,7–11] do indicate that the use of lightweight parts has grown significantly to this end. Improved mechanical properties such as strength, fracture toughness, and fatigue resistance, are crucial for guaranteeing the structural integrity and safety of aeronautical parts [1,7]. This is because aircraft and spacecraft typically operate under numerous types of harsh conditions such as extreme temperatures, significant levels of radiation, large variations of pressure, and mechanical stress. Additionally, these structures experience different types of loads such as turbulence, lift and drag forces, gust loads, operating loads, launch loads, gravitational loads, thermal loads, and pressure loads. Therefore, ensuring that materials can withstand these conditions and loads is critical [7]. Additionally, taking account of the degree of flexibility in designing and customising lightweight parts and choice of materials, typically influences how aeroplanes and spacecraft are built to be aerodynamically as well as structurally efficient [2]. This adaptability additionally allows for generation of new designs using additive manufacturing technologies such as, selective laser sintering, fused deposition modelling, electron beam melting, and stereolithography, as well as advanced metal alloys (such as titanium alloys, aluminium-lithium alloys, superalloys, and magnesium alloys) and polymers (including carbon fibre-reinforced polymers, polyimides, and thermoplastic polymers) that were previously unattainable using conventional manufacturing technologies and materials

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[3,8,10]. Ongoing research and development in materials science have contributed to the evolution of novel lightweight parts with good mechanical properties [1,2,7,11]. Carbon-fibre composites [1], titanium alloys [8,9], and improved aluminium alloys constitute just a few types of the often-adopted materials for lightweight structures. These materials have a good combination of strengths and low densities, whilst improving the stringent standards of aerospace applications [4,8,9]. Apart from uses in commercial aviation, lightweight parts with improved mechanical properties are of great importance in space exploration. This is because spacecraft with weight constraints require materials that are capable of withstanding the harsh conditions of travelling in space while remaining as lightweight as possible [12–14].

Hierarchical structuring is often adopted to improve the mechanical properties of lattice parts such as the HCs. This approach calls for embedding smaller unit cell shapes into larger structures, resulting in a multi-scale structure (see Fig. 1) [15]. This figure shows four categories of commonly used approaches in designing hierarchical structures based on polygonal shapes.

The four hierarchical design approaches mentioned in the previous figure (see Fig. 1), namely the vertex-based, cell-wall-based, fractal-based, and spiderweb-based observed are inspired by nature, where hierarchical structures are prevalent in numerous biological materials such as insects, arachnids, mammals and plants (see Fig. 2), which are known to have good mechanical properties and are also efficient in the use of materials [15].

Hierarchical HC designs can be enhanced with regard to their mechanical properties such as strength, stiffness, and toughness by incorporating different sizes of hollow structures. This is achieved by efficiently designing to distribute loads across different levels of the structures [16–21]. Hierarchical HCs are capable of achieving high strength with minimal material usage via optimisation of their configuration at multiple levels, resulting in them being ideal for lightweight yet robust applications. This is crucial in applications requiring impact resistance, such as the development of crash-worthy materials for automotive and/or aerospace applications [19,20]. Material properties could be engineered with different levels of hierarchical structuring as well. The external surface of the macro-structures, for instance, could be engineered to provide overall strength, whilst the meso-structures and micro-structures could be designed to improve flexural ability or energy absorption [19]. Hierarchical structures as well aid in the reduction of sensitivity to bend-dominated deformation. Different levels within a hierarchical structure add to bending force resistance, resulting in the entire structure being more resistant to such deformation [16,18–20]. The choice of polygonal unit cell shape introduced at the vertices or walls of the parent structure influences the effectiveness of the entire structure under imposed loads. There are gaps in literature with regard to the highest order of hierarchy that is physically attainable for hierarchical HCs built irrespective of the different polygons used.

This article provides an extensive review of hierarchical honeycomb (HC) structures, with a primary focus on their behaviour, design effectiveness, and applications, particularly in aerospace industries. The paper begins by reviewing recent and relevant studies on hierarchical HCs. This review of open access literature includes advances in the comprehension of the mechanical behaviour, material properties, and structural advantages associated with hierarchical HCs, thereby providing a valuable reference for researchers in search of updates on the newest findings in this area of research. Through discussions of the constraints associated with the order of hierarchy and geometric characteristics, the work covers a fundamental aspect of HC design that is not often thoroughly reviewed. This particular focus sheds fresh insights into the limitations and promises of hierarchical structuring in HCs. Highlighting the application of hierarchical HCs in the aerospace sector gives practical value to theoretical and experimental results. In this respect, the review underlines the general engineering implications as well as the advantages of these structures, thus bridging the gap between research and application in industry. The review of AM technologies that are used to build hierarchical HCs touches on a recent and still emerging trend. Additive manufacturing is a fast-expanding field, and its integration with HC design could result in significant advances in the effectiveness of manufacturing, customisation of parts, and efficient usage of material. The discussion presented in this paper on this topic points to the resolution of present capabilities and thus creates prospects for future applications, while providing a road map for blending AM with HC design. Such examination of upcoming research paths and breakthroughs provides a prospective point of view. This is important in establishing the primary objectives for extending studies and technological advances, as well as fostering novelty and ongoing advancement in the development and application of hierarchical HCs.

Some of the primary design-to-mechanical testing procedures that are used for hierarchical HCs (see Fig. 3), in addition to their applications in engineering. The graphi graphical representation in the figure summarises the associated and latest challenges and points out some anticipated future avenues for resolving them.

In particular of this current review on hierarchical HCs, the current challenges attached to their additive fabrication and the future progress are pointed out. To comprehensively understand hierarchical HCs, it is essential to first examine their current challenges and potential advancements in deformation behaviour. Addressing these challenges provides a foundation for deeper analysis, enabling their effective implementation in engineering applications.

A systematic review of literature on hierarchical HCs was conducted by searching academic databases, including Scopus, PubMed, and Web of Science. The review focused on experimental and modelling-based studies examining the mechanical properties, deformation behaviour, fatigue behaviour, and biological compatibility of HCs. Particular attention was paid in the review to AM, material properties observed in materials such as Ti6Al4V, composites, polymers, and shape memory alloys, and as well as engineering applications of hierarchical HCs. Only studies directly addressing hierarchical HC design, fabrication, and application were included, while reviews and theoretical papers were excluded unless offering relevant insights.

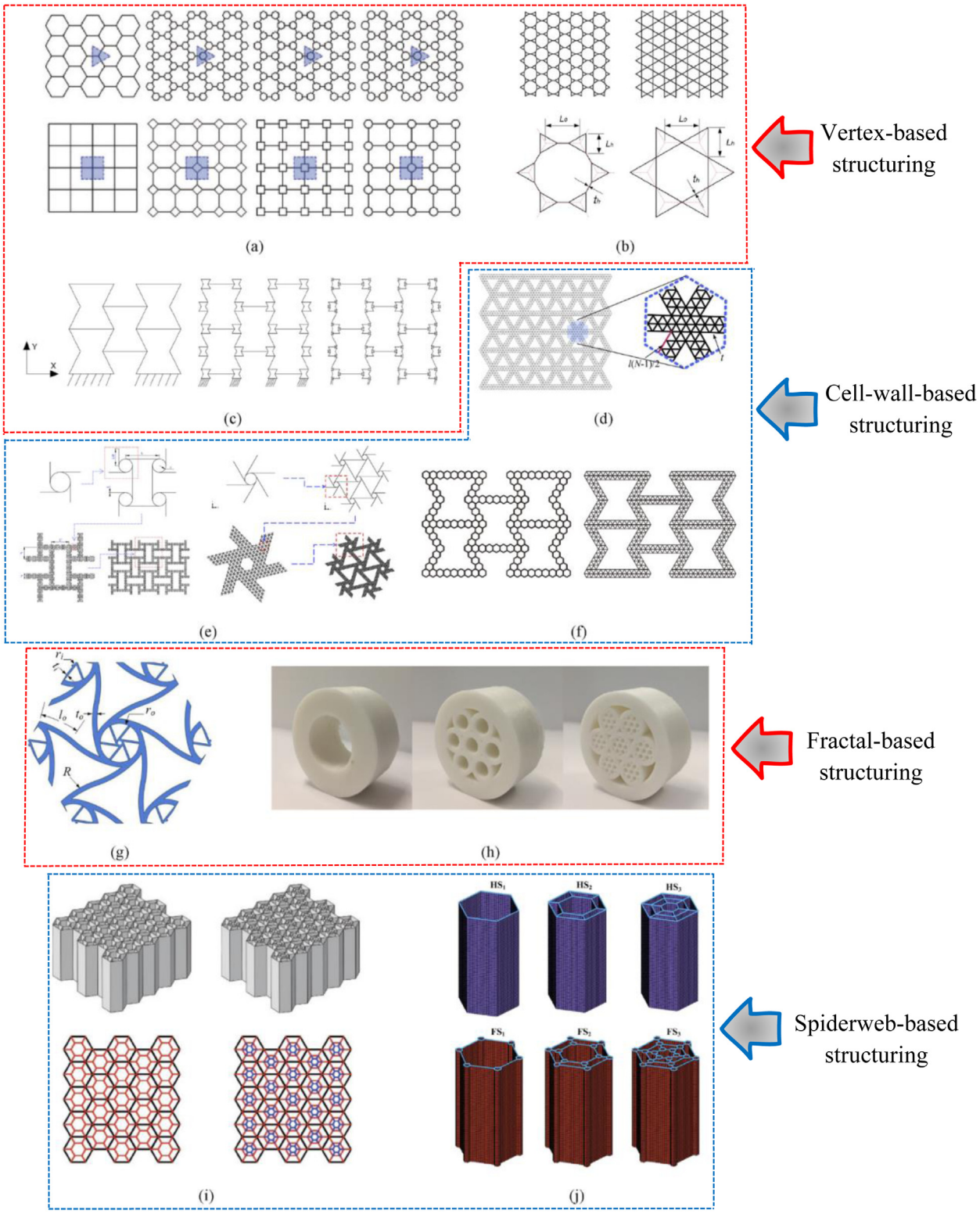


Fig. 1. Types of hierarchical polygonal shapes. (a-b) vertex-based hierarchical polygonal structures, (c) vertex-based hierarchical re-entrant HCs, (d) cell-wall-based hierarchical triangle honeycomb (HC), (e) cell-wall-based hierarchical using tetra-chiral and hexa-chiral HCs, (f) cell-wall-based hierarchical re-entrant HCs, (g) fractal-based hierarchical hexa-chiral HC, (h) fractal-based hierarchical circular polygon structures, and (i-j) spiderweb-based hierarchical hexa-chiral HCs [15].

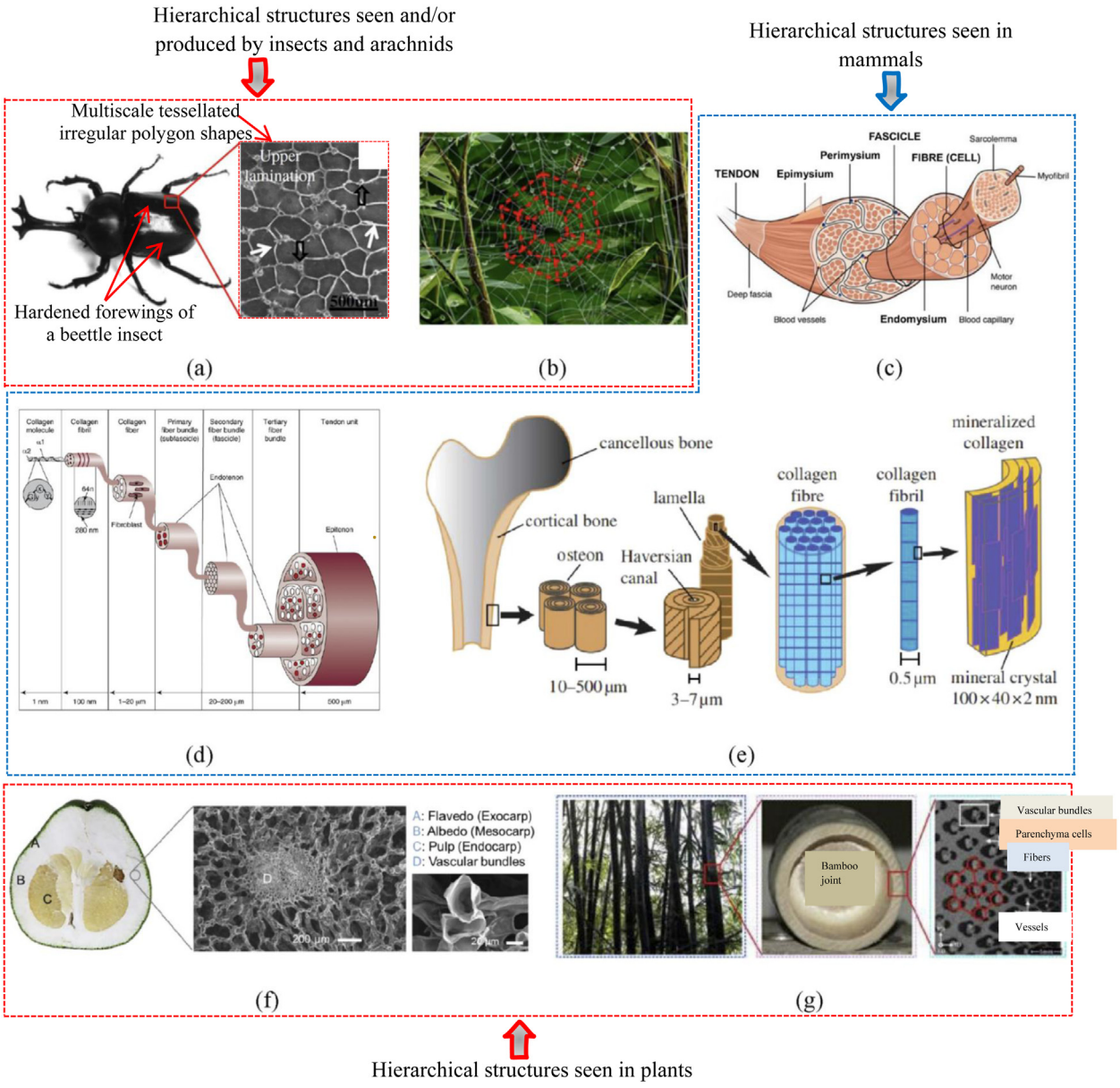


Fig. 2. Hierarchical structures observed in biomaterials. (a) beetle elytron scales with multiscale tessellated irregular polygon shapes, observed on the hardened forewings (elytra) of beetle insects, (b) spiderweb designed with polygon shapes of different scales by a spider, (c) various levels of hierarchical levels seen in a skeletal muscle, (d) various hierarchical levels, from nano-to-micro scales observed in a tendon tissue, (e) macro-to-nano hierarchical structuring of a femur bone, (f) pomelo peel with hierarchical structures observed from the flavedo to the vascular bundles seen at the micro scales, and the (g) bamboo tree with hierarchical scales seen after analysing a bamboo joint, in which the hierarchical structures form part of the vascular bundles, parenchyma cells, fibers and vessels [15].

The review included publications from 2010 to 2024, with older studies included for their foundational contributions. After screening, 160 papers were reviewed, with 125 meeting the inclusion criteria for final analysis to summarise key findings and trends in this review.

2 Deformation behaviour of hierarchical honeycombs

The deformation behaviour of hierarchical HCs is a function of complicated interactions of numerous aspects their internal structures that are influenced by their distinct nature. Understanding how hierarchical HC structures deform under different loading conditions is crucial for maximisation of their performance in a variety of engineering applications.

Hierarchical HCs are referred to as multiscale structures, which implies that they are built up of nested unit cells that come in different sizes [15,20]. Their hierarchical structuring allows them to efficiently distribute loads while resisting deformation [20]. During deformation, smaller unit cells within larger ones often fail or deform first, whereas larger unit cells remain relatively intact. Such a

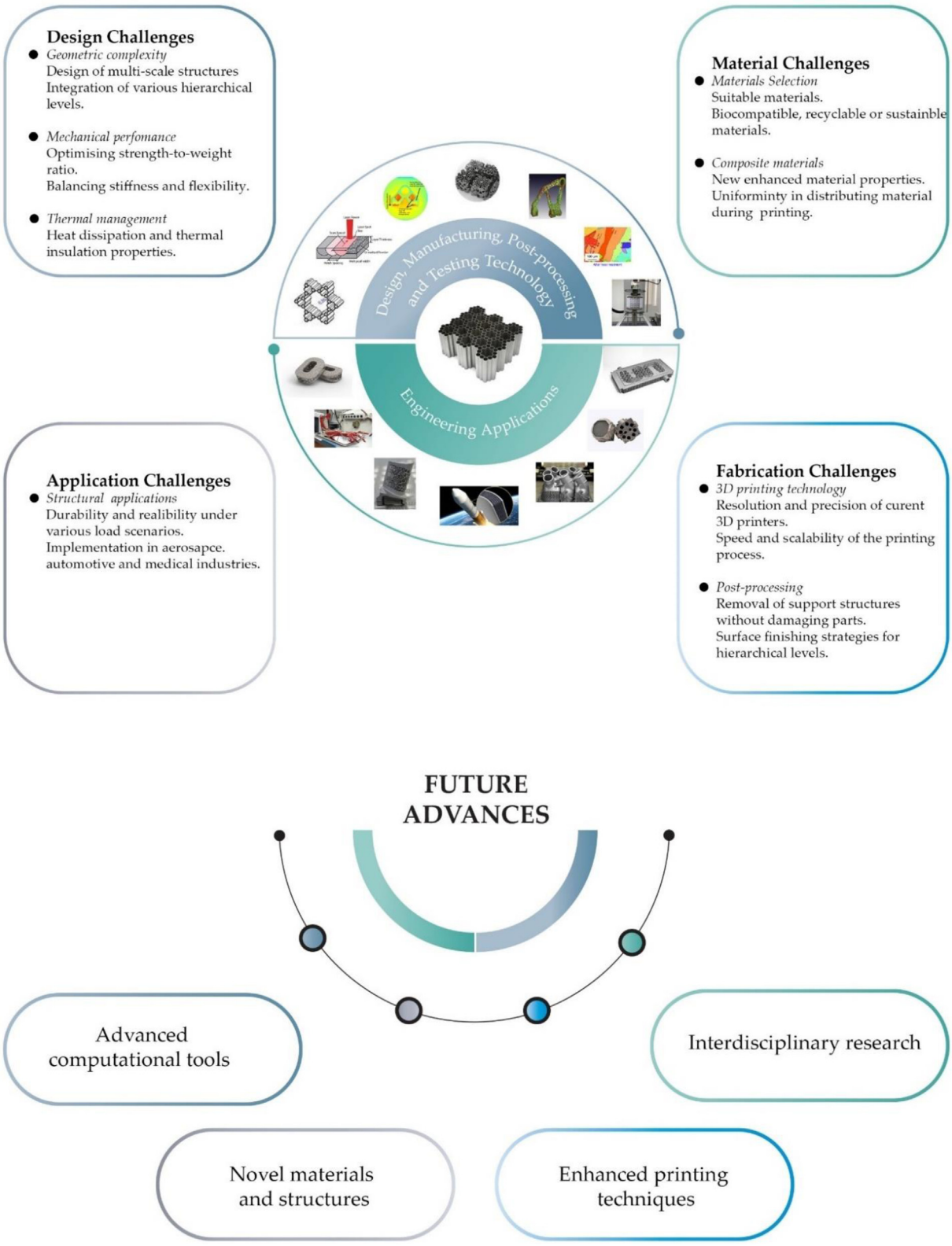


Fig. 3. The central circular diagram highlights key technologies for designing, manufacturing, post-processing, and testing hierarchical HCs, along with their engineering applications. Surrounding this diagram, the four text-filled boxes categorically outline primary challenges related to the design, materials, manufacturing, and applications for hierarchical HCs. A half-sphere diagram and the four elliptical text boxes underscore the areas of focus for the future advancements in designing hierarchical HCs.

deformation mechanism allows hierarchical HCs to redistribute loads that are imposed on them. The external forces applied on such structures are typically transferred from collapsed or deformed unit cells to neighbouring unit cells that are still intact [15,21–32]. This load redistribution strategy serves a primary objective of safeguarding against localised failure and preserving the structural integrity of the entire hollow structure [26–32].

Ajdari et al. [33] created a hierarchical HC by substituting all three-edge joints of the regular hexagonal hollow build with smaller hexagons. Their work demonstrated that hierarchical HCs with one or two levels have a stiffer modulus of elasticity than regular HCs with the same relative density. The rise in performance comes from the hierarchical structures that effectively re-distribute loads and increase load-bearing capacity by adding smaller hexagons at three-edge joints. These revised configurations lower stress concentrations at critical points, such as the vertices, and introduces multiple load paths, increasing stiffness and minimising deformation under loading. However, the effects of thermal expansion, changes in temperature, and environmental factors such as humidity and corrosion on hierarchical HCs were not examined in their work. Comprehending the effects of these factors is critical in ensuring the strength and stiffness of these structures in different mechanical loading scenarios. To fully grasp the bounds of hierarchical HCs, extensive experimental testing, materials advancement, and the development of new manufacturing technologies are required. Sun et al. [34] built an anisotropic multifunctional hierarchical HC (AMHH) by substituting the solid cell walls of the basic anisotropic HC (OAH) with the same-weight isotropic substructures referred to as triangular or Kagome HCs. This structuring approach yields two types of AMHH structures. The study showed that triangular HC substructures can enhance the in-plane stiffness of AMHH by 1.5 to 100 times, depending on the thickness-to-length ratio (t/l) of the oblique cell wall and the relative density of the OAH. This enhancement, ranging from 1.5 to 100 times, is because of the effective redistribution of the material that is afforded by the hierarchical structuring, which exploits the inherent mechanical advantages of periodic substructures while adhering to the set constraints in weight. The improvement of stiffness has a direct connection to the oblique cell walls' ratio t/l and the relative density of the OAH, as both of these parameters dictate the distribution of load and the mechanics of deformation within the hierarchical structure. However, the influence of boundary conditions and edge or vertex effects on the mechanical characteristics of these hierarchical structures were not thoroughly reviewed in their study nor have they in open literature. Such considerations could result in significant effects on performance, particularly for engineering applications with edge or vertex constraints. The absence of extensive analysis of edge and vertex effects could affect the dependability and safety of AMHH structures in engineering applications. Unexpected failure or drop of performance tend to occur close to edges or vertices, where high-stress concentrations typically occur. This calls for thorough studies on the effect of edges and vertices on the general strength and stiffness of AMHH structures. This would include work to predict the distribution of stresses and identification of regions of possible of failure. In addition, research to devise strategies for lowering high-stress concentrations close to edges and vertices should be carried out. This may entail tailoring the configuration of the substructures or adding new support parts.

Chen et al. [35] investigated the in-plane compressive behaviour of a novel hierarchical lattice structure formed by substituting cell walls in regular HCs with triangular lattice topologies. The research conducted revealed that hierarchical HCs have high energy dissipation and shape integrity at strains of up to 60% during cyclic loading. Their experimental and numerical findings also suggest that this peculiar mechanical behaviour is accounted for by a hierarchical structure controlled by the triangular lattice's slenderness and the shape memory effect caused by thermal and mechanical compression. The triangular lattice's slender geometry increases pathways for deformation and distributes the stress effectively, leading to improved energy absorption. Additionally, the shape memory effect, triggered by thermal and mechanical compression, allows the material to recover its original form after unloading, maintaining structural integrity over repeated cycles. These findings imply that hierarchical lattice designs leveraging slender geometries and smart material properties can be optimised for high-performance energy-absorbing applications, such as mitigation of impact and biomechanical implants. Hierarchical lattice structures of different wall thickness formed by replacing cell walls in regular HCs with triangular lattice shapes (see Fig. 4) [35]. This figure showcases experimental results, underlining the deformation behaviour, failure patterns, and stress-strain response curves, in conjunction with numerical findings that show deformation behaviour, distribution of stress, and stress-strain response curves of hierarchical lattice structures.

The graph on the far left (see Fig. 4a) shows highly oscillated responses in stress-strain curves, whereas the curves on the far right show non-oscillated responses. The highly oscillated responses in stress-strain curves usually correspond to separate deformation events, such as buckling or collapse of particular cells or layers in the structure. Such a stress-strain trend tends to coincide with dynamic or cyclic loading scenarios, which cause oscillations as the structure goes through repeated deformation and recovery processes. In the case of non-oscillated responses, the curve clearly transitions from elastic to plastic behaviour, with the material deforming plastically after yielding. The absence of oscillations indicates uniform deformation without significant structural instabilities or localised failures. This stress-strain trend often has to do with static or monotonic loading conditions. The fundamental lack of Chen et al.'s work [35] is that it concentrates solely on the in-plane compressive behaviour of hierarchical lattice structures under cyclic loading, without considering their performance in complex multi-axial loading scenarios or long-term durability in changing environments. To close these gaps, this review suggests optimising the design by integrating thin-walled geometries and smart material

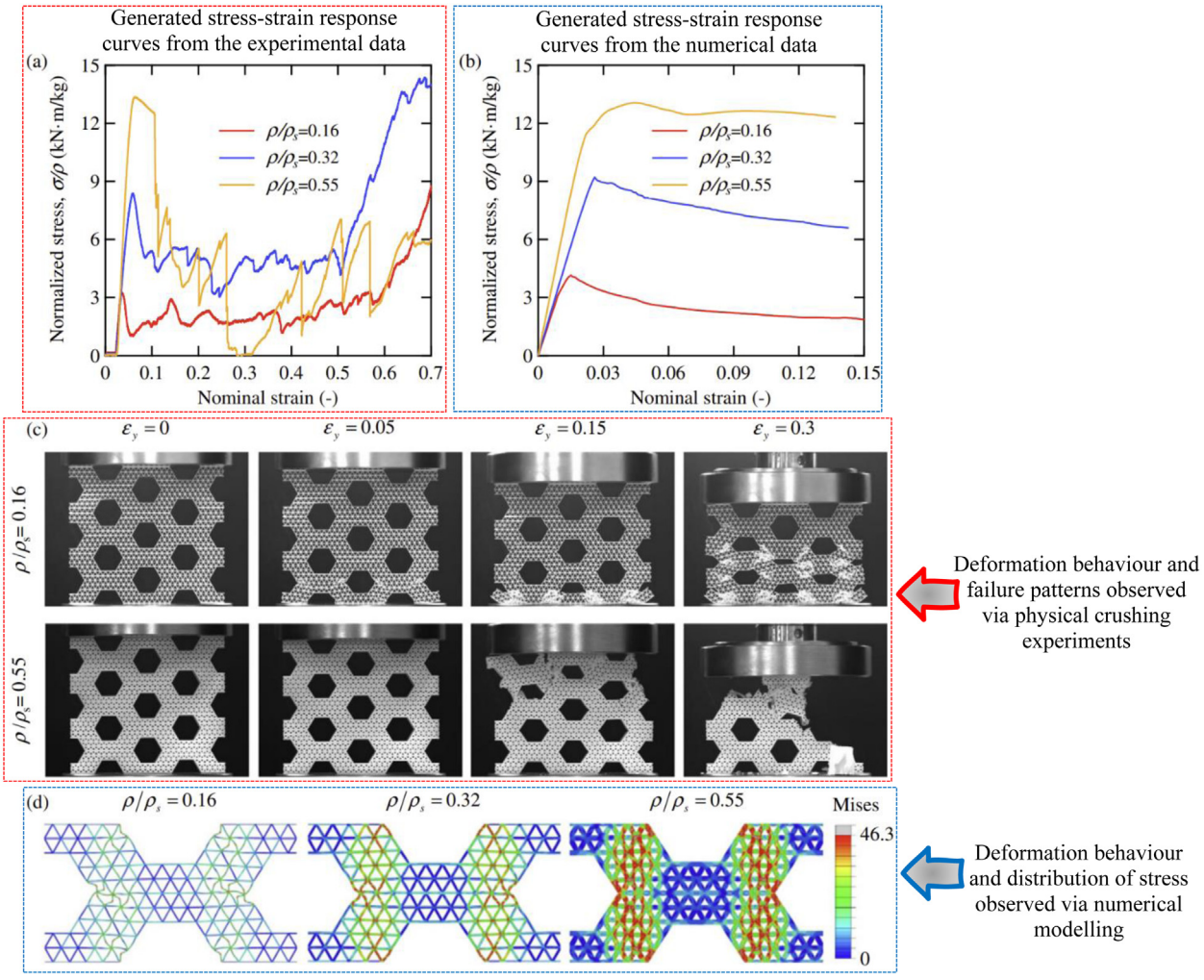


Fig. 4. Experimental and numerical findings of built hierarchical lattice parts, formed by replacing the cell walls with small-scaled triangular hollow structures of different wall thickness. (a) stress-strain response curves generated from crushing experiments of the hierarchical lattice structures, (b) stress-strain response curves generated from numerical crushing of hierarchical lattice structures, (c) deformation behaviour and failure patterns captured in experimental crushing of hierarchical lattice structures, and (d) deformation behaviour and distribution of stress observed in numerically modelling hierarchical lattice structures [35].

properties, such as shape memory effects in multi-axial loading scenarios, to improve energy absorption, impact resistance, and structural integrity, particularly for biomechanics and materials resistant to impacts.

Song et al. [36] built bioinspired hierarchical polygon hollow metastructures with good mechanical characteristics. Their hierarchical squared hollow structure with circular holes reduced stiffness by 0.84%, strength by 19.38%, and improved energy absorption by 199.67%. When compared to the regular parent hollow structures, the hierarchical HC with circular holes improved stiffness by 1.06%, reduced strength by 5.55%, and improved energy absorption by 345.24%. Analysis of the reviewed study reveals that the hierarchical squared hollow structure with circular holes resulted in a slight decrease in stiffness and strength, which is likely due to the redistribution of material and stress loads, yet significantly enhanced energy absorption, likely due to the enhanced load-bearing capacity. The load-bearing capability is associated with the geometry of the structure. In contrast, the hierarchical hollow structure with circular holes improved stiffness slightly, reduced strength moderately, and significantly enhanced energy absorption, implying that the intricate geometry of the hierarchical structure better managed stress and deformation during impact, leading to increased energy dissipation. Though this particular hierarchical design provides significant energy absorption benefits, its lowered strength and stiffness must be carefully addressed when examining possible applications, especially for load-bearing and high-strength conditions. Further studies should focus on tailoring such structures for a more balanced enhancement in all mechanical properties.

The walls of individual unit cells in hierarchical HCs typically experience buckling or collapse during deformation [15,26]. This behaviour allows the honeycomb to absorb energy by converting mechanical energy into deformation of the unit cell walls [15,20,27,28]. The hierarchical structuring of unit cells often determines the

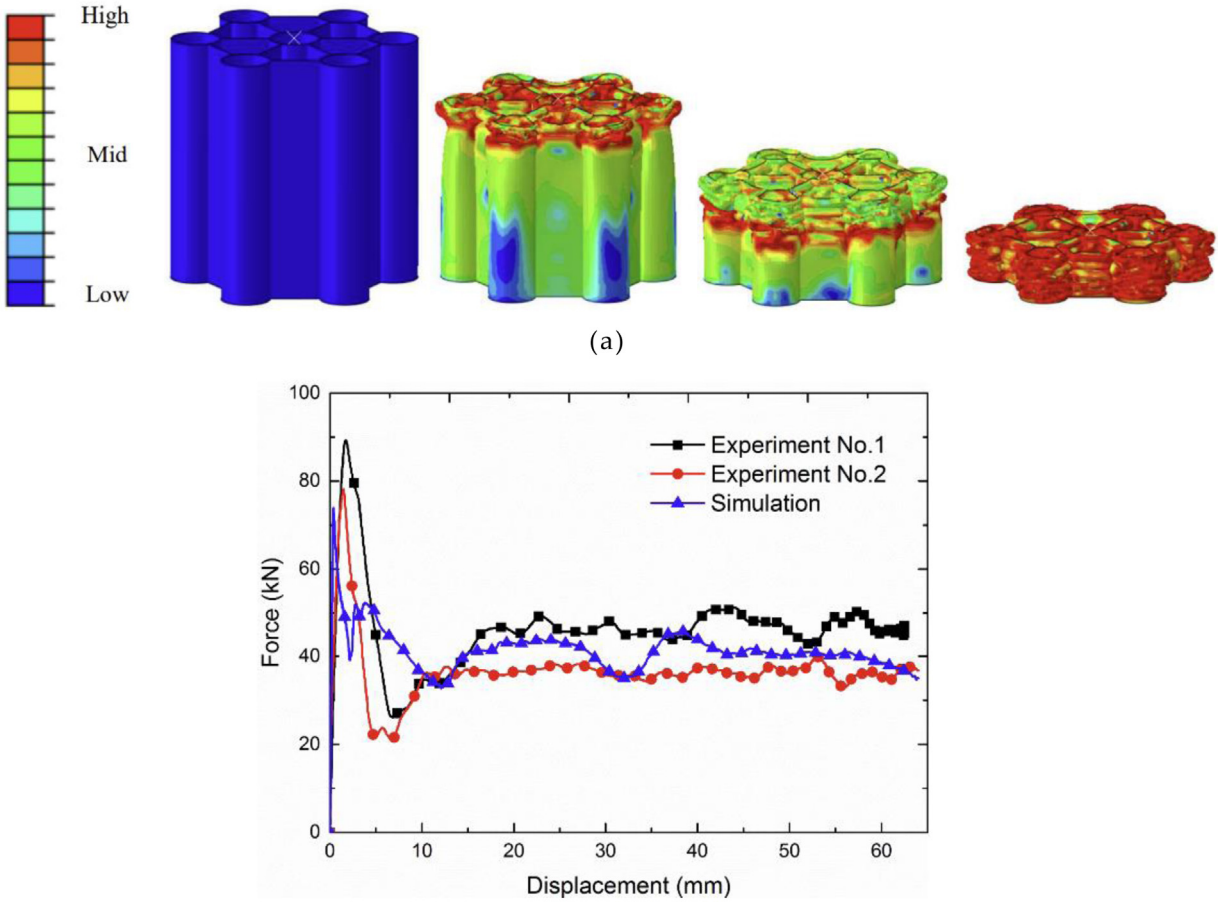


Fig. 5. (a) Numerical findings showing, (a) the graphic progressive diamond mode of failure mechanism; and (b) the generated load-displacement curve based of experimental and numerical crush tests describing the gradual diamond deformation mechanism of a non-self-similar nested HC under dynamic extruded shell in-plane crushing loads [37].

order and extent of cell wall buckling and collapse, which in turn influences the structure's overall deformation behaviour [15,22]. The hierarchical structuring of HCs not only allows for efficient energy absorption via phenomena such as cell wall buckling, and unit cell collapse but also through plastic deformation [15]. This is the primary reason why hierarchical HCs are typically adopted in engineering applications that require impact protection such as automotive crash structures and protective gear [15,20–22]. Hu et al. [37] reported a novel non-self-similar nested HC constructed using an aluminium alloy and inspired by bamboo's vascular bundles. This structure consisted of one centred circular tube and six encircling circular tubes. The drop-weight test for impact applied on this HC showed its failure mechanism to be a gradual diamond mode, exhibiting the highest specific energy absorption of 29.3 J/g. The vascular bundles provide a balance of strength and flexibility in the natural bamboo structure design, which is modelled by the structuring of a center circular tube encircled by six surrounding tubes. Progressive deformation becomes apparent by the drop-weight impact test's reported gradual diamond mode failure, which enhances the effectiveness of energy dissipation. This failure pattern is favorable, limiting catastrophic failure and allowing energy absorption over an extended period. The structure's design maximises energy absorption per unit mass by optimising the distribution of material, resulting in a high specific energy absorption (29.3 J/g). The gradual diamond deformation mechanism or failure mode (see Fig. 5) [37], suggesting a controlled deformation pattern is clearly ideal in structural parts wherein progressive energy dissipation is crucial to avoid catastrophic failure.

The drop-weight impact test is a specific type of dynamic loading condition. The structure's behaviour under other loading conditions such as cyclic loading, and high-strain-rate impacts was not examined and could result in different findings. Further analysis under numerous types of loading conditions, including cyclic loading, high-strain-rate impacts, and multi-axial loads, could provide a broader understanding of the structure's behaviour. Sun et al. [38] investigated HCs with 1st- and 2nd-order hierarchical configurations under out-of-plane loading. They observed that the two orders of hierarchy enhanced the specific energy absorption by over 80% and 180%, respectively. This enhancement can be ascribed to the hierarchical structures' superior capabilities in distributing and dissipating energy over traditional lattice structures.

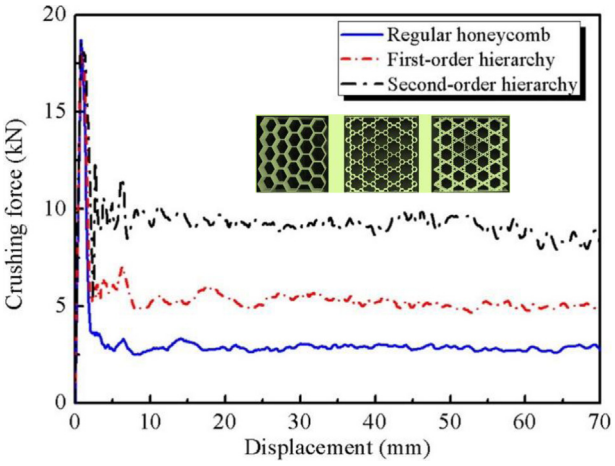


Fig. 6. Load-displacement curves for numerical out-of-plane crushing of vertex-based hierarchical HCs built using aluminium alloy [38].

While the 2nd-order hierarchy adds more complexity and encourages a progressive deformation mechanism that better controls the energy absorption process. The 1st-order hierarchy possibly expands the effective area of contact and introduces more channels for distribution of stress. Their corresponding load-displacement curves are also presented (see Fig. 6) [38].

The significant rise in specific energy absorption by a value of 80% and 180% for 1st- and 2nd-order hierarchical HCs, respectively, suggests that these structures could prove useful in applications that require the absorption of high amounts of energy, such as protective materials and crashworthy structures. Their study, however, fails to include an analysis of the surface roughness of the manufactured parts. Surface roughness in additive-produced hierarchical HCs, particularly metallic parts, often gets higher as the grade of hierarchy increases, which could result in a substantial impact on their energy absorption behaviour. This is an area of possible future work. Zhang et al. [39] added a triangular structure into a regular HC via a vertex substitution strategy. They reported that the plateau stress and specific energy absorption were improved by 127% and 109%, respectively, in the in-plane ribbon direction. For the identical characteristics highlighted in the preceding sentence, an improvement of 122% and 108% was found along the in-plane width direction, respectively, whereas improvements of 30% and 34% were obtained for out-of-plane loading. Improvements in the plateau stress and specific energy absorption, specifically 127% and 109%, respectively, in the in-plane ribbon direction, can be attributed to the increased structural stiffness and the better distribution of load achieved by the triangular configurations, which resulted in better deformation characteristics and more efficient energy dissipation. The notable enhancements in the in-plane width direction (122% improvement in plateau stress and 108% in energy absorption) implies that the triangular structure facilitates greater load-bearing capacity by re-structuring the overall geometry and improving the resistance to shear forces. However, the more modest improvements observed under out-of-plane loading (30% and 34%) suggests that the triangular modification predominantly influences in-plane mechanical properties, as the out-of-plane performance is more dependent on the overall structural height and less influenced by in-plane geometry re-configurations. These findings highlight the efficacy of the vertex substitution strategy in optimising the performance of hierarchical HCs for specific directional loading conditions. The different works of these sets of authors on crushing behaviour, with reference to out-of-plane and in-plane loading are also highlighted in the two following figures, respectively (See Fig. 7 and Fig. 8) [39].

The analytical models adopted in the work conducted by Zhang et al. [39] describe the crushing behaviour of the produced intricate structures based on general mathematical representations of the absorbed energy EA and specific absorbed energy SEA. The analytical models often adopted during the crushing process of the discussed structural parts are expressed in equations (1) and (2), respectively.

$$EA = \int_0^{\delta} F d\delta \tag{1}$$

$$SEA = \frac{EA}{M}. \tag{2}$$

The symbols F, $d\delta$, M in these two equations represent the crushing load, crushing displacement and overall mass of the structural part, respectively. Given the way various parts of the structural frame are connected via the nodes, these models could fail to predict the complicated behaviour that is often observed at the vertices of such systems. It is imperative to extend work into building advanced analytical models that account for the complex interactions between structural parts at the vertices. Effective application of advanced behaviour models could provide fresh insights into how the complex connectivity at the vertices influences the behaviour of hierarchical HCs. He et al. [40] designed a spiderweb-based hierarchical HC by incorporating a smaller hexagon structure into the centre of the parent structure, emerging with a hexagonal network design. Their numerical findings indicated that the specific energy absorption of 1st- and 2nd-order hierarchical HC increased by 62.1% and 82.4%, respectively. This approach exploits the hierarchical architecture, where the addition of a secondary structure within the primary hexagon improves the material's energy distribution and dissipation during deformation. The enhanced energy absorption observed in the 1st- and 2nd-order hierarchical HCs (62.1% and 82.4%, respectively) is attributed to the creation of additional load-bearing paths and multi-level mechanisms of energy dissipation. Impact forces are transferred through the nested structures, resulting in a more gradual and efficient process of deformation, thus improving energy absorption. The numerical findings underscore the superior mechanical performance of the hierarchical design, as the smaller hexagonal structures reduce localised stress concentrations and facilitate more uniform energy dispersion, rendering it ideal for applications requiring optimised crashworthiness and impact resistance. The numerical models, however, were generic and failed to

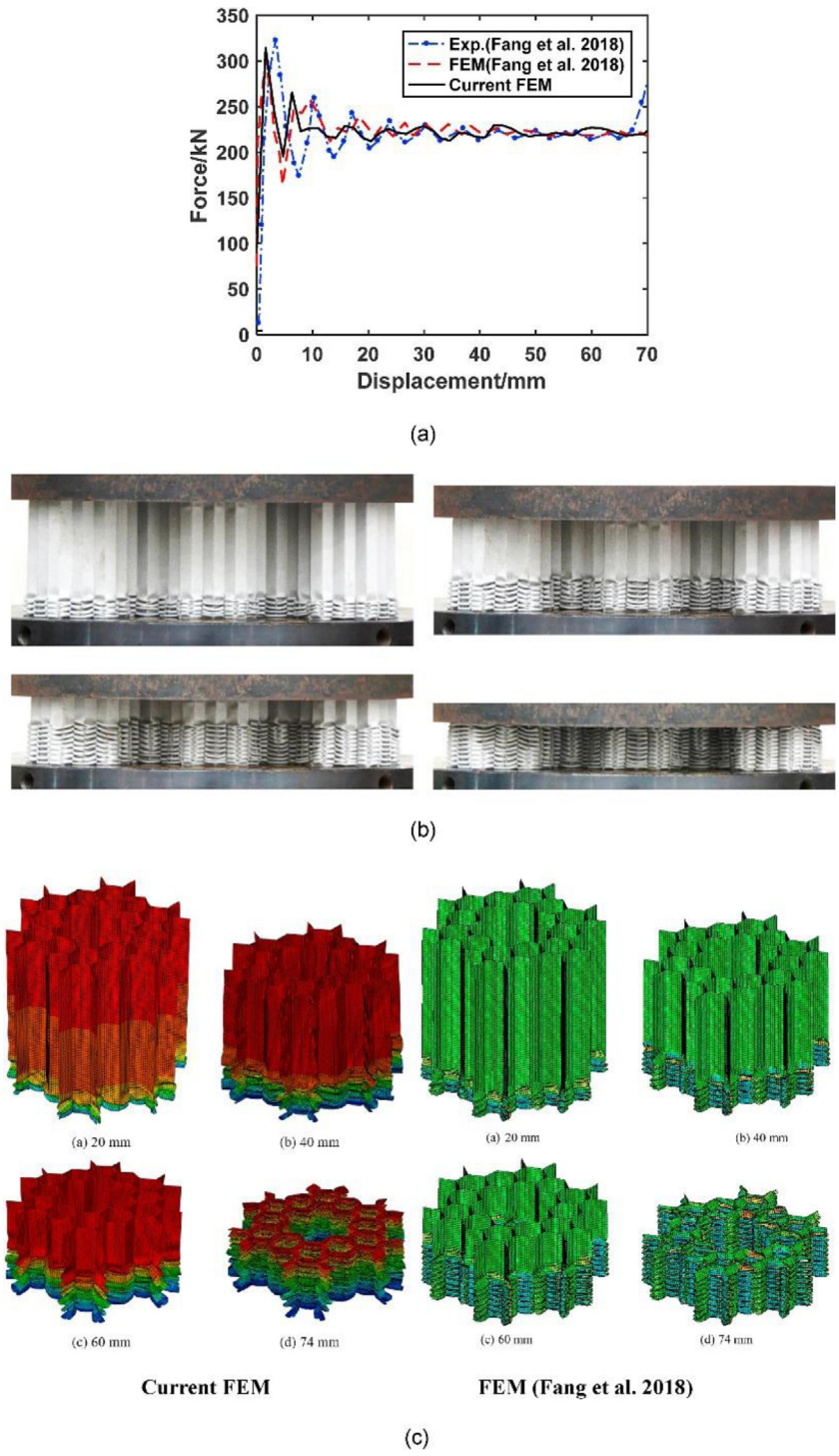


Fig. 7. Experimental and numerical findings for out-of-plane crushing of vertex-based hierarchical HCs with triangular substructures built using aluminium material [39].

account for particular engineering conditions such as dynamic impact, changing temperatures, and lastly strength, all of which have significant effects on the effectiveness of hierarchical structures in engineering applications in the aerospace, automotive, offshore, and medical fields. These studies should be extended in order to integrate the numerical models to specific engineering uses such as scaffolding in bones, and crash behaviour of bumpers in automobile bumpers. For the latter case, crash behaviour models tailored to automotive uses could lead to the development of lighter, more effective automobiles that meet safety criteria, while reducing the consumption of fuel and emissions, particularly in sports racing cars. For the case of medical fields, there are prospects already in progress for

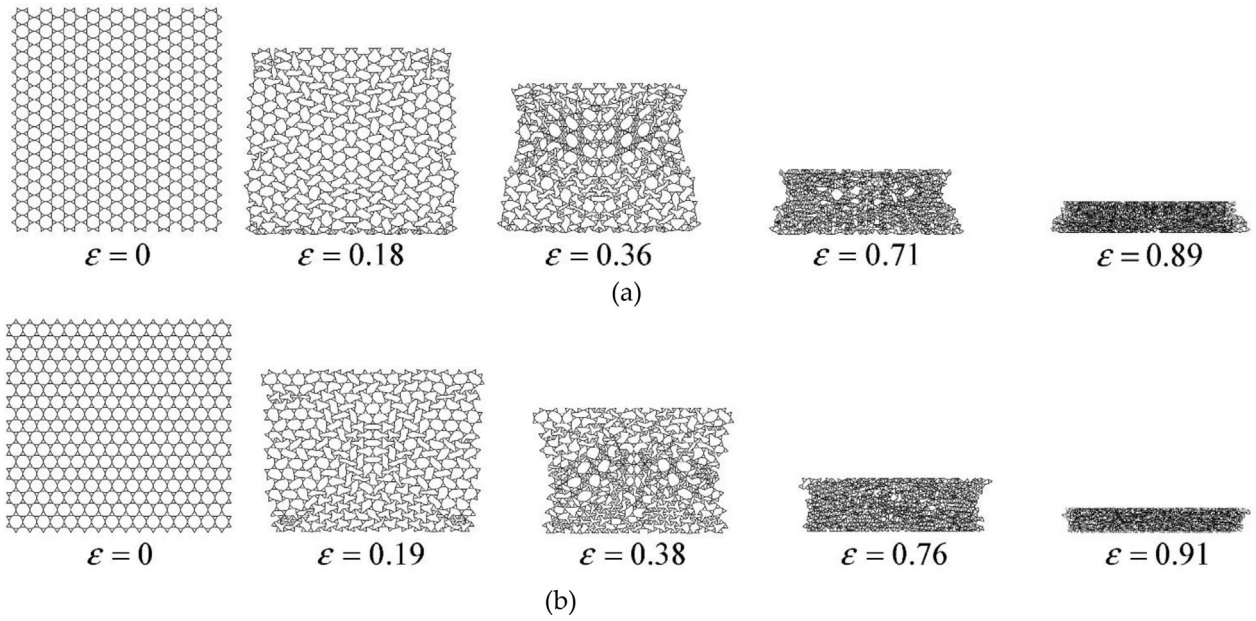


Fig. 8. Deformation histories generated for in-plane crushing of a line beam vertex-based hierarchical HC with triangular substructures, along the (a) width and (b) ribbon directions, respectively [39].

using modern algorithms to develop new surgical techniques and materials, extending past the boundaries of what is currently attainable in regenerative medicine and orthopaedics. Tan et al. [41] generated a new hierarchical re-entrant HC design by substituting the cell wall of auxetic HC with regular hexagonal and triangular polygon shapes. Their numerical findings suggested that, as contrasted with regular re-entrant HC, hierarchical HC improved specific energy absorption and crushing force by approximately 292% and 298%, respectively, under a quasi-static loading condition. The observed 292% improvement in specific energy absorption and 298% increase in crushing force can be attributed to several key factors. The hierarchical cellular structure facilitates efficient transfer of load and energy dissipation during compression. The use of regular hexagonal and triangular polygons improves the stability and uniformity of cell walls, optimising interactions between cells and their deformation under quasi-static loading. Additionally, the modified cell geometry enhances stiffness and strength, enabling higher crushing forces while allowing for a more controlled mechanism of failure. This combination of optimised cell design, hierarchical architecture, and deformation behaviour results in significantly improved energy absorption and crushing performance. A key limitation of the study by Tan et al. [41] is the focus on quasi-static loading conditions, which may not fully represent the dynamic or impact loading scenarios that real-world applications often involve. The performance of the hierarchical re-entrant honeycomb (HC) design under dynamic or varying loading rates, such as those encountered in high-impact or trauma situations, remains uncertain. To address this limitation, future studies could investigate the behaviour of the hierarchical HC under dynamic loading conditions using high-speed testing or numerical modelling tools such as ABAQUS, that account for varying strain rates, to better understand its potential for real-world applications. Qi et al. [15] compared and categorised mechanical parameters of normal classical HCs and their related hierarchical configurations. They made available bar graphs to describe mechanical performance ratios. As reported in their findings, the specific absorbed energy, modulus of elasticity, and compressive strength increased by 590% with ID 24, 1230% with ID 28, and 316% with ID 23, respectively (see Fig. 9) [15].

The findings, presented via bar graphs of mechanical performance ratios, showed a significant increase in specific absorbed energy, modulus of elasticity, and compressive strength for hierarchical HCs. Increases of 590% (ID 24), 1230% (ID 28), and 316% (ID 23) were observed, attributed to the hierarchical design's optimisation of the distribution of the material, improving energy absorption through a multi-scale structure that effectively dissipates forces. The improvements in modulus of elasticity and compressive strength are likely due to the enhanced load-bearing capacity of the hierarchical architecture, which provides superior mechanical reinforcement compared to traditional HCs. The variation of performance across different IDs suggests that structural parameters such as cell size, shape, and hierarchy level significantly influence mechanical behaviour, underscoring the potential of customised hierarchical designs for advancing cellular material performance.

The hierarchical configuration of unit cells often results in anisotropic deformation behaviour, which implies that the mechanical behaviour of the hierarchical honeycomb differs based on the chosen direction of loading [15,27–32]. Anisotropic properties result from asymmetry in unit cell configurations and sizes within the overall structure [15,26–28]. Therefore, understanding and characterising this heterogeneity is often crucial when predicting and optimising the structural performance of hierarchical HCs in engineering applications. The deformation behaviour of hierarchical HCs is as well dependent on the size

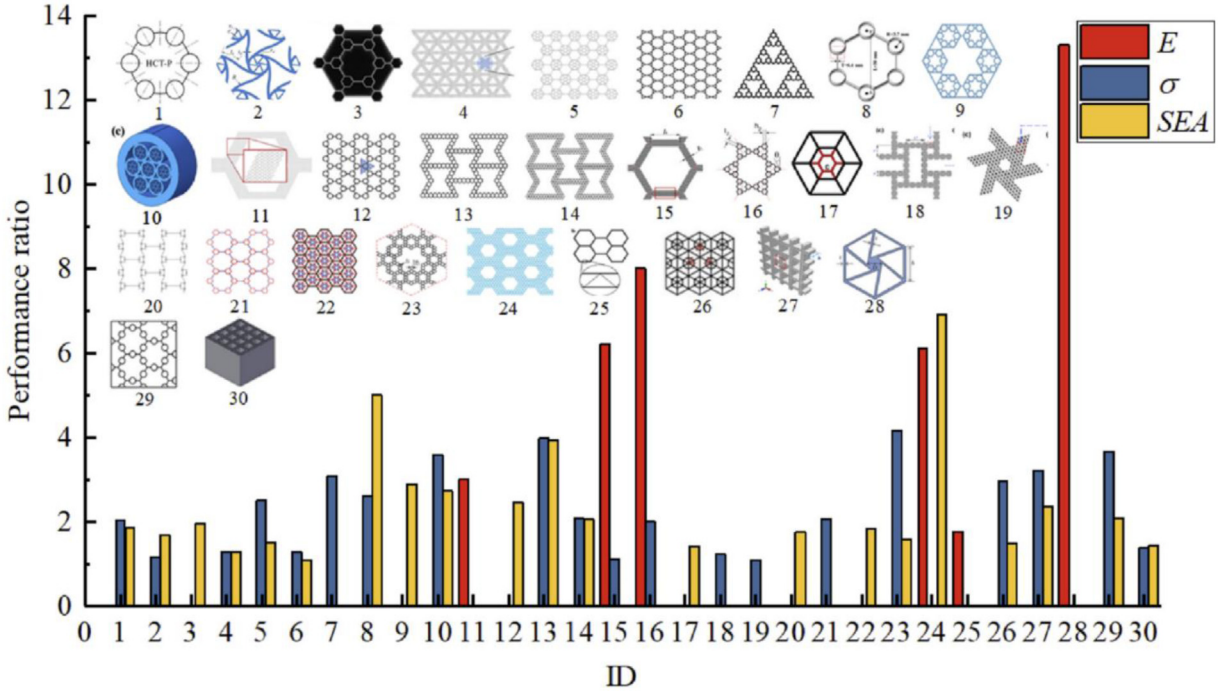


Fig. 9. Mechanical characteristics of regular HCs and hierarchical HC builds and their performance ratios [15].

and configuration of the unit cells built at different length scales [15,26]. Mechanisms of deformation at smaller scales differ from those at higher scales, causing the hierarchical honeycomb's overall mechanical behaviour to change [15,26,31,32,42]. It is important to account for scale dependency as it is critical for accurate modelling and prediction of the behaviour of hierarchical HCs subjected to different loading conditions. Chen et al. [43] developed numerical models that describe better thermal resistance in hierarchical HC lattice metamaterials. Their analysis of heat transfer of these structures suggested that hierarchical HCs are capable of thermal anisotropy, while also enhancing thermal resistance because of their hierarchical structuring and topologies. Their findings are primarily theoretical and are based solely on numerical models. The hierarchical design inherently creates multi-scale pathways for heat transfer, which disrupts thermal conduction and enhances resistance while allowing directional control of heat flow, leading to thermal anisotropy. The findings are theoretical, grounded in validated numerical models that simulate heat transfer mechanisms, emphasizing the role of hierarchical architecture in manipulating thermal behaviour. Through successful numerical analysis of their findings, Chen and colleagues [43] suggested through numerical modelling strategies that, the hierarchical HC lattice metamaterials could be used to design cutting-edge thermal management systems in electronics, thus improving overall effectiveness of devices via tailored thermal resistance and anisotropy. This, however, requires further validation by physical experiments with ideal operating conditions to confirm the predicted thermal resistance and anisotropy in engineering applications of such hierarchical HC lattice metamaterials.

Despite their hierarchical structure and inherent toughness, hierarchical HCs are prone to fracture and do fail under extreme load conditions [15,24,25,30–32]. Comprehending the fracture and failure mechanisms of these structures is crucial when designing engineering structures required to withstand specific loading conditions, while guaranteeing safety and reliability in structural applications. Techniques such as finite element analysis (FEA) and multiscale modelling are crucial and popular for providing quick understanding and prediction of the deformation behaviour of hierarchical HCs, compared to experimentation [15,26–29]. Finite element analysis models are capable of representing the complex interactions between unit cells across different length scales, thus providing insight into mechanisms of deformation and failure possibilities [26]. Experimental validation of these computational predictions is however critical in guaranteeing the fidelity of models and expanding the comprehension of hierarchical honeycomb deformation behaviour in structural applications [15,30–32]. Ryvkin and Shraga [44] used numerical modelling approaches to examine the effect of self-similar hierarchical structuring on the brittle fracture behaviour of a two-dimensional HC. Their work revealed that a HC with a higher level of hierarchy has greater fracture toughness than one with a lower level. They also suggested that hierarchical architecture has a clearer effect on HCs with lower relative densities associated with thin walls that are prone to fail at lower loads. A comparison of Mode I fracture toughness between 2nd-order hierarchical HCs and regular HCs revealed a 5.4% increase for $\rho = 0.115$ and 39% for $\rho = 0.0289$, respectively. The findings by Ryvkin and Shraga [44] can be attributed to the inherent ability of self-similar hierarchical structuring to redistribute stress and mitigate

crack propagation more effectively than regular lattice structures. The greater fracture toughness observed in higher-order hierarchical HCs stems from their multi-scale architecture, which enables the redistribution of load across multiple structural levels, thereby delaying crack initiation and propagation. This effect is more pronounced in HCs with lower relative densities, as the thin walls in these structures are more susceptible to localised stress concentrations and early failure in the absence of hierarchy. The striking increase in Mode I fracture toughness with decreasing density (5.4% for $\rho = 0.115$ and 39% for $\rho = 0.0289$) illustrates the amplified benefits of hierarchy at low densities, where structural optimisation plays a critical role in enhancing mechanical resilience under conditions for brittle fracture. Their work was limited to Mode I and II fracture toughness and therefore, ignored the implications of additional fracture modes such as Mode III, also referred to as out-of-plane shear or tearing mode, which can occur in engineering applications. The emphasis on Mode I and II fracture toughness limits the comprehension of how hierarchical configuration influences overall fracture toughness under different loading conditions. Therefore, further studies are required to investigate its effects on this other mode of fracture. Ajdari et al. [33] investigated the mechanical properties of hierarchical HCs with self-similar microstructures using theoretical, experimental, and numerical modelling methods. Their analysis showed that the primary and secondary HC structures were 2.0 and 3.5 times harder than regular HCs, respectively. The superior mechanical properties of hierarchical HCs reported in their study can be attributed to the multi-scale load-distribution mechanism enabled by self-similar microstructures. The primary HC structure exhibits enhanced stiffness due to the introduction of additional load paths within the hierarchical structure, enabling more effective redistribution of the stress compared to regular HCs. In the secondary HC structure, further cell subdivision increases the density of structural parts, leading to higher stiffness and greater resistance to localised deformation. Theoretical modelling captured the scaling laws governing these hierarchical enhancements, while numerical models validated the distribution of stress and mechanisms of deformation, highlighting improved stress concentration factors. Experimental results corroborated these findings, demonstrating that hierarchical configurations optimise the distribution of the material, mitigate failure-prone regions, and achieve significantly higher levels of hardness than non-hierarchical counterparts. The capacity of the modelling and experimental methods could, however, limit the degree of detail and resolution of the investigated hierarchical microstructures. A limited resolution could result in a lack of comprehension of how microstructural details at various scales influence overall mechanical properties, which can result in missing crucial insights. To overcome the constraints of scale and resolution, prospective studies should use advanced methodologies that are capable of better resolution and multiscale analysis. This allows for an extensive understanding of how microstructural characteristics affect overall mechanical performance.

2.1 Mechanisms of deformation at different scales of hierarchical structures

Hierarchical HCs exhibit unique mechanisms of deformation at various scales due to their intricate architecture. These structures are typically designed to absorb energy and distribute stresses effectively across multiple levels, from the macro-, meso- to micro-scale [45,46].

2.1.1 Micro-scale mechanisms of deformation

At the microscale, deformation of HCs begins with elastic deformation of the cells. As the load increases, the thin cell walls experience bending and compression, governed by the material properties like stiffness and yield strength [20,46–49]. When the load surpasses the yield strength, plastic deformation occurs, leading to micro-cracking along the cell walls or at the cell junctions. This progression may eventually lead to shear failure, particularly at the joints between cells, where localised failure is more likely, especially in materials with low shear strength [50]. Hierarchical features, such as thinner walls or smaller nested cells, can further influence the mechanisms of deformation, enhancing or diminishing the overall structural integrity depending on the design [20,47,51].

2.1.2 Meso-scale mechanisms of deformation

At the meso-scale, mechanisms of deformation emerge as interactions between cells and cell clusters influence the overall behaviour of hierarchical HCs. Key mechanisms include buckling of cell struts, where compression causes the struts to buckle depending on their length-to-cross-sectional area ratio and material properties [52–56]. Additionally, contact between cells can occur under load, leading to localised deformations such as cell-wall flattening or inter-cell friction [57]. Hinge mechanisms, often integrated at cell junctions, enable controlled rotation, facilitating energy dissipation through angular displacement and provide structural flexibility. These mechanisms contribute to the progressive deformation and adaptation of structures under load [32,58–61].

2.1.3 Macro-scale mechanisms of deformation

At the macro-scale, HC structure's mechanisms of deformation evolve to manage large-scale external loads, influencing its stability and performance. Global bending and flexure occur as the structure deforms elastically under initial loading, transitioning to plastic deformation once yield stress is exceeded. Localised damage or micro-cracking at smaller scales can lead to the propagation of cracks, with cracks travelling through the hierarchical levels, causing progressive failure. If a critical load is surpassed, yielding and failure initiate at the weakest points (vertices in this case) and spread to stronger areas (cell walls in this case), often resulting in catastrophic failure. The hierarchical design aids in the absorption of energy and distribution of stress, mitigating the severity of failure by facilitating progressive deformation across scales [20,47,51,62,63].

2.1.4 Deformation progression between the three (micro-, meso- and macro) scales

At lower loads, the structures exhibit elastic deformation across all scales, with micro-scale bending and compression inducing minor local distortions in the cell walls. As the load increases, deformation progresses from the micro to the meso-scale, where the bending of individual struts lead to buckling and hinging behaviour at the cell level. This escalates the prominence of cell interactions. At higher loads, macro-scale bending or buckling occurs, and cracks initiated at lower scales propagate, ultimately causing global failure of the hierarchical HC structure. A review of the literature available to the authors reveals a gap in detailed schematics or figures describing mechanisms of deformation across micro-, meso-, and macro-scales in porous and multiscale lattice structures. Although mechanisms of deformation are discussed, visual representations and systematic correlations are generally limited to macro-scale or homogenised models, which constrains understanding of hierarchical behaviour under diverse loading conditions [20,46–49,52–57,62,63].

2.2 Critical analysis of the contradictions and discrepancies in the reviewed literature

Despite the current state of developments relating to the mechanical performance of hierarchical HCs, inconsistencies persist in reported findings, particularly regarding the effects of hierarchy levels, boundary conditions, material-specific behaviour and limitations in modelling approaches.

2.2.1 Influence of hierarchical levels

Ajdari et al. [33] demonstrated that introducing hierarchical levels significantly enhances stiffness and load-bearing capacity by effectively redistributing loads and reducing stress concentrations. Similarly, Sun et al. [38] reported notable improvements in specific absorption of energy with 1st- and 2nd-order hierarchies under out-of-plane loading. However, discrepancies arise in the magnitude and nature of these enhancements, as Ajdari et al. primarily attributed improvements of stiffness to the redistribution of load through smaller hexagonal substructures, while Sun et al. emphasized energy absorption gains, which do not necessarily correspond to increased stiffness. These variations may stem from differences in testing conditions, such as static versus dynamic loading, as well as variations in manufacturing techniques and material properties employed in the respective studies.

2.2.2 Directional loading performance

Zhang et al. [39] reported significant improvements in plateau stress and energy absorption for in-plane loading due to substitutions of triangular vertices. Conversely, these enhancements were modest under out-of-plane loading. This contrasts with the findings of Hu et al. [37], who reported exceptional efficiency in the absorption energy under dynamic in-plane loading using bamboo-inspired designs. These conflicting findings highlight the dependency of hierarchical performance on geometry and load orientation. While triangular modifications enhance in-plane stiffness and energy dissipation, they may compromise out-of-plane performance due to reduced structural height.

2.2.3 Mechanisms of deformation and failure modes

The gradual diamond-mode failure observed by Hu et al. [37] is consistent with the mechanisms of progressive dissipation of energy, while Chen et al. [35] reported highly oscillatory stress-strain curves under cyclic loading, indicative of localised buckling and collapse. These contrasting behaviours of deformation suggest that the hierarchical structure plays a dual role, influencing both the absorption of energy and the propagation of failure throughout the material. However, the lack of a unified framework for analysing deformation across studies complicates the ability to generalise the findings.

2.2.4 Role of boundary conditions

The role of boundary conditions is often overlooked. Sun et al. [34] demonstrated enhancements in stiffness through uniform substructures but failed to analyse the effects of edge- and vertex-constraints. High-stress concentrations near edges and vertices are known to cause premature failures, yet systematic investigations aimed at mitigating these effects are sparse.

2.2.5 Material-specific responses

Hierarchical designs incorporating shape memory alloys (SMAs) or other smart materials, as highlighted by Chen et al. [35], exhibit significant potential in cyclic loading applications. However, the recovery behavior of SMAs varies across studies, which may be attributed to inconsistencies in thermal cycling protocols or microstructural variations induced by different manufacturing processes.

2.2.6 Discrepancies in mechanical performance metrics

Tan et al. [41] reported a significant increase (292% and 298%) in SEA and crushing force under quasi-static loading due to hierarchical re-entrant designs. However, Qi et al. [15] highlighted variations in performance based on structural parameters such as cell size, geometry, and hierarchy level. For instance, their bar graphs showed mechanical improvements of 590% (SEA), 1230% (modulus of elasticity), and 316% (compressive strength), with performance heavily dependent on the hierarchical configuration and scale. These discrepancies suggest that uniform metrics for evaluating mechanical performance are lacking, leading to difficulties in cross-study comparisons.

From the review in this section of the paper, it is clear that the deformation behaviour of hierarchical HCs is typically influenced by their multiscale design, load transfer mechanisms, anisotropic characteristics, scale dependency, energy absorption capacities, and fracture behaviour. Engineers

could benefit more by developing hierarchical HCs with specific mechanical properties for a variety of engineering applications, such as lightweight parts, impact-resistant materials, and energy-absorbing structures, by fully comprehending and characterising these aspects. Building upon the insights gained from the deformation behaviour and mechanical performance of hierarchical HCs, the next section delves into the challenges and constraints in determining the achievable order of hierarchy, which is critical for optimising their design and functionality across diverse engineering applications.

3 Constraints in determining the order of hierarchy attainable for hierarchical honeycombs

The order of hierarchy in connection to hierarchical HCs refers to the structuring of smaller polygonal cell sizes within HC structures [26]. The numerous factors that determine the level of hierarchy attainable in hierarchical HCs are pointed out in this section.

The properties of materials that are used to fabricate hierarchical HCs have a direct influence on the order of hierarchy attainable. Comprehending the mechanical, thermal, and electrical properties of the selected materials at different hierarchical orders is crucial when undertaking thorough studies on their use in specific engineering applications. This is because the behaviour of the structures under external loading and environmental conditions is determined by the choice of materials [20,26,32]. Furthermore, the availability of ideal materials that can be efficiently processed while maintaining the desired levels of hierarchy could pose a challenge as well [26,28,32].

Limitations of imaging tools are typically pointed out in literature [15,19–29] and are often related to their limited capacities in observing and analysing structures at a scale that is desired. This is because HCs have complicated hierarchical features at different lengths and scales that can prove challenging to capture in detail [15,20,26]. Conventional ways of analysis and measurement can fail to include the entirety of the scale spectrum, resulting in their inability to accurately capture every level of the hierarchy, as well as the relationships between the differently scaled structures [15,26]. The complex configurations observed within HCs tend to occur at micro and nanoscales [15,20]. To accurately analyse these structural parts, high-resolution imaging methods are typical required. Thus, limitations in imaging methods can make it challenging for researchers to get comprehensive details regarding smaller-scale structures that are built-in [20,26]. Given the broad range of the structures, understanding, and determining the relationships and different hierarchical configurations across different scales is often challenging [20]. Numerous numerical values are reported in available literature [64] that are comparable to the typical scales encountered and the level of detail of microscale and nanoscale imaging systems for analysing structures such as hierarchical HCs. For instance, the optical microscopy technique offers a resolution of 200 nm and is ideal for examining structures larger than 1 μm. The imaging approach is effective for analysing structures in the micrometre range, but less so for greater levels of detail [65]. In contrast, a scanning electron microscopy (SEM) imaging system has a higher resolution (in the range of 0.5 to 4 nm) as compared to optical microscopy, with axial and lateral resolutions of 500 nm and 200 nm, respectively [20,66,67]. This makes SEM ideal for thorough microscale investigation [66,67]. Transmission electron microscopy (TEM) works well for nanoscale imaging. The TEM imaging technology has resolutions of up to 0.1 nm, facilitating for analysis of atomic-scale structures [66]. Atomic force microscopy (AFM) gives comprehensive surface topography with resolutions ranging from 1 to 10 nm, which is useful for analysing the characteristics of surfaces at the nanoscale [68]. Cryo-electron microscopy (Cryo-EM) allows for imaging with near-atomic resolution, generally around 0.2 nm. It is typically required for examining the accurate structures of proteins and other biological macromolecules [69]. Comprehending the constraints and capabilities of these imaging techniques is crucial to determining the best strategy for examining hierarchical HC structures at various scales. Blending different imaging strategies often yields a more comprehensive view of these complicated systems.

Numerical modelling of hierarchical HCs involves dealing with complex geometries and multi-scale interactions. Accurate modelling requires advanced numerical methods such as finite element methods, finite difference methods, finite volume methods, boundary element methods, multigrid methods, adaptive mesh refinement, mesh-free methods, level set methods, and discontinuous Galerkin method, as well as optimisation algorithms and significant computational resources, such as high-performance computing (HPC) systems, graphics processing units (GPUs), cloud computing resources, advanced software tools, large memory and high-speed networks, and algorithm optimisation. It may prove challenging to generate feasible computer models for simulating and predicting the hierarchical levels of HCs [26–32]. This is because of challenges in building accurate numerical models for hierarchical HCs that accurately describe complicated geometries and multi-scale interactions, retain high resolution, and use advanced numerical strategies. These characteristics, together with the need for significant processing resources and extensive optimisation algorithms [70]. The complex nature of hierarchical HCs requires a delicate balance between computational efficiency and model-fidelity, necessitating advanced methodologies and large computational capacity. This is because for engineering applications, striking a balance between accuracy and processing efficiency is crucial [20]. Additionally, toward an in-depth comprehension of HC hierarchies, information gathered from experiments and numerical models must be integrated. However, challenges often arise when incorporating experimental and numerical data such as data discrepancies, data processing and comprehension, quantification of uncertainty, validation, boundary

and first conditions, variations of scale, complicated geometries, and material characteristics. As a result of this, assuring accuracy across different levels, and validating the generated models can pose an additional challenge [20,26].

The large amount of data generated by imaging and modelling techniques requires complicated processing and analysis approaches, even for simple lattice structures [15]. Developing algorithms that are capable of controlling complex hierarchical data sets is presently an ongoing challenge. Furthermore, incorporating data from different sources, such as imaging, numerical modelling, and field research, requires advanced integration and analysis strategies [15,19,20,23–25]. Thus, building comprehensive models that account for the intricacies of hierarchical HCs is even more difficult.

To achieve hierarchical structures in HCs, accurate manufacturing methods are required as well. Conventional methods, such as casting, extrusion, or moulding, have challenges duplicating complex hierarchical structures, particularly at lower scales [24–26]. Designing complex hierarchical structures throughout the manufacturing process requires a high level of precision and precise tolerances. A significant number of additive manufacturing (AM) machines are used for building objects with dimensions in the range of centimetres or larger with accuracies that exceed a few hundredths of a millimetre [71]. Maintaining these tolerances gets more challenging as the HC structure's complexity and scale increase [26]. Scalable manufacturing procedures for HCs with hierarchical features are crucial for engineering applications. Scaling can pose problems in terms of consistency, quality control, and cost-effectiveness. Ensuring the quality and consistency of HCs, particularly those with intricate hierarchies, presents quality control issues during the manufacturing process [42,72,73]. Defects or differences from the original design tend to be challenging to detect. To achieve specified functionality, some HCs may call for the integration of different materials with different properties [73,74]. It can be difficult to link or connect these materials whilst maintaining the intended hierarchy. Customising hierarchical HCs for particular uses often requires a degree of tailoring and flexibility in design. Manufacturing methods can encounter challenges when tackling varying design requirements and hierarchical feature changes. Materials and manufacturing methods must be chosen on the basis of objectives for sustainability and environmental requirements [42,72–75]. Developing eco-friendly ways of manufacturing while preserving the desired hierarchy adds a level of complexity to manufacturing [75].

The numerous challenges associated with determining and achieving the desired order of hierarchy in hierarchical honeycombs highlight the intricacies involved in their design, analysis, and manufacturing processes. Despite these challenges, the unique properties of hierarchical HCs have proven to be transformative, particularly in high-performance engineering applications such as those found in the aerospace industry.

4 Contributions of using hierarchical honeycombs in aerospace industries

Hierarchical HCs are useful for engineering applications in aerospace industries, particularly in areas related to structural design [15]. The HCs, in particular hierarchical HCs, are acknowledged for their good strength-to-weight ratios [26]. In aircraft, weight reduction is crucial for improving the fuel efficiency and overall performance. Using hierarchical HCs in structural components such as wings, fuselage, and tail sections of airframes can assist in attaining lightweight designs without compromising strength [76–78]. The hierarchical HC core adds strength and rigidity whilst maintaining weight to a minimal. Hierarchical HCs are often integrated into sandwich panel designs. Sandwich panels are built of a lightweight core material (such as the HC or polygonal hollow structures) positioned between two outer layers. This design is good for providing structural integrity, thermal insulation, as well as reducing the weight of the structure [76,78–80]. Aerospace applications of hierarchical HCs also include aircraft interiors, such as flooring and cabin panels [61]. The intricate designs exhibited in hierarchical HCs not only lower the weight of components but are also appealing to the eye [15,20]. This frequently draws customers to use aircraft as a form of transportation, resulting in increased income from adopting such advertising strategies [20].

The HCs have hierarchical configurations of numerous levels that could assisting in improving the impact absorption and crashworthiness of the parts. This characteristic is useful in aerospace applications, particularly when designing parts that must withstand impacts, such as landing gear parts and structural parts designed for improving passenger safety [20,76–78]. Hierarchical HCs can provide effective thermal insulation as a result of their polygonal hollow structures. This is useful in aerospace, particularly for parts that are subjected to high changes in temperature, such as engine components, satellite structures, or spacecraft [78,80]. When adequately built, hierarchical HCs can additionally influence aerodynamic performance. This is because hierarchical HCs are often used to optimise airflow and reduce drag in aerodynamic surfaces such as winglets or fairings [79,80].

Hierarchical HCs are ideal for supporting antennas and other communication devices on aerospace vehicles such as satellites and unmanned aerial vehicles (UAVs) due to their lightweight but structurally resilient integrity [80]. Fairings are widely used in the aircraft industries to protect payloads during launch and atmospheric re-entry [77,79,80]. The lightweight and robust characteristics associated with hierarchical HCs are particularly useful when designing spacecraft fairings [78,79]. Hierarchical HCs' lightweight characteristics can be used to build gasoline tank structures as well. This in turn, assists in reducing overall weight while improving fuel efficiency in aircraft [80].

Evidently, increased strength-to-weight ratio, improved impact resistance, and greater thermal or acoustic properties are potential advantages of hierarchical HCs [15,20,76–80].

The specific physical characteristics and mechanical properties of the hierarchical HCs determine the particular applications in aerospace engineering. Despite their numerous advantages, implementing hierarchical HCs in aerospace applications presents several challenges, particularly when leveraging AM techniques, necessitating innovative solutions to fully realise their potential.

5 Challenges and the way forward with hierarchical honeycomb design for additive manufacturing

The design of hierarchical HCs for additive manufacturing (AM) has benefits as well as drawbacks. The method referred to as AM, or 3D printing, has become popular for the production of hierarchical HCs because it allows for the fabrication of complicated geometries and structures. The following are some challenges and prospects related to the design and manufacture of hierarchical HCs using AM.

Choosing the right materials for hierarchical HCs that are compatible with AM technologies could prove challenging. The material must not only meet structural criteria, but it must additionally be printed with the chosen AM process [81]. Recent advancements in AM have improved the selection of materials for complex and multiscale structures [82–86]. Innovations such as preceramic polymers enable the fabrication of intricate ceramic components via AM techniques like fused filament fabrication (FFF), followed by pyrolysis to transform printed polymers into fully dense ceramics with tailored properties. Composite feedstocks with micro- and nanoscale fillers further enhance mechanical performance; for example, incorporating boron nitride nanobarbs into epoxy feedstock anisotropically increases strength and stiffness along fiber orientations, enhancing the structural integrity of printed HCs. Additionally, advancements in robocasting, a direct ink writing technique, leverage shear-thinning inks to broaden compatibility of materials, enabling the generation of complex architectures with diverse compositions. These breakthroughs collectively advance the feasibility of producing hierarchical HCs that meet both structural and manufacturing demands. Designing an optimised hierarchical HC calls for finding the correct balance between structural integrity and manufacturability. Complex geometries could present challenges in terms of building and removing support structures, printing time, and accuracy in capturing geometrical details [87–90]. High-resolution printing is required to flesh out hierarchical HC designs. Misalignment of layers, surface roughness, and inadequate resolution all can influence the hierarchical HC's structural performance [90–92]. Complex geometries typically call for support structures during the AM process. Removing these supports without damaging the delicate hierarchical HC often is time-consuming and could affect the final part's quality [12,88]. Optimisation of AM process parameters, such as layer thickness, printing speed, and temperature, is a time-consuming process and is critical in attaining the desired mechanical properties and surface polish in hierarchical HCs [12,62,93,94]. Current developments in AM have also enhanced the design and fabrication of complex and multiscale structures such as hierarchical HCs, focusing on optimising complex geometries while addressing challenges of manufacturability [84,85]. Density-based topology optimisation has emerged as a critical method for creating self-supporting structures, thus minimising wastage of materials, and enhancing the efficiency of manufacturing by integrating constraints that ensure structural integrity [86]. Concurrently, innovations in 3D parameterised lattice microstructures and the development of topology-optimised, easily removable supports have reduced post-processing efforts and facilitated efficient removal using standard tools [82–85]. High-resolution AM techniques, such as two-photon polymerisation and laser powder bed fusion (LPBF), enable intricate designs with minimal surface roughness and high dimensional accuracy, mitigating issues like misalignment and limitations of resolution [95–98]. Additionally, advancements in soluble support materials and process parameter optimisation, aided by AI and machine learning algorithms, have streamlined production, enhancing mechanical performance and quality of surfaces [95,97]. Hybrid manufacturing approaches, combining AM with precision machining, further improve the manufacturability and reliability of these complex HC geometries [20,95,96]. Together, these developments balance structural performance and manufacturability, advancing the physical implementation of hierarchical HCs.

Recent advancements in implant materials address fatigue failure, a critical factor in the longevity of medical implants [99–102]. Sun et al. [103] investigated the fatigue behaviour of porous Ti6Al4V-6Cu alloy fabricated via selective laser melting (SLM), tested in air and a 0.9 wt% NaCl solution to model physiological conditions. The obtained results showed that high stress levels accelerate the initiation of fatigue cracks (FCs), while the propagation of cracks is exacerbated in the NaCl solution due to corrosion fatigue, resulting in predominantly intergranular fractures. The Ti6Al4V-6Cu alloy demonstrated superior fatigue strength and life compared to Ti6Al4V, attributed to the Ti2Cu phase near grain boundaries and the zigzag path of FCs, which enhance resistance to the growth of cracks. These results highlight the alloy's potential for the production of durable medical implants. The study additionally underscores the role of alloying elements and microstructural design in improving fatigue performance under corrosive physiological conditions. The addition of Cu to the alloy enhances both antibacterial properties and the material's resistance to fatigue degradation, making it a suitable candidate for long-term implant applications. This underscore the importance of integrating multifunctionality into multiscale structures, ensuring their mechanical resilience while addressing challenges of biological compatibility. Slámečka et al. [104] demonstrated exceptional fatigue performance of titanium scaffolds with hierarchical porosity produced via direct ink writing (DIW). Scaffolds with open intrastrand porosity (14.3%) showed a tenfold increase in fatigue life over those with compact strands (5.9%), achieving normalised fatigue strength of 62% of the yield strength after 10^6 cycles. This improvement arises from crack growth shielding mechanisms that slow the propagation of

cracks, extend crack paths, and enhance energy absorption, positioning DIW-fabricated scaffolds as robust candidates for cyclic load-bearing applications. These principles can inform hierarchical HC designs, where tailored porosity optimises the distribution of the stress and structural resilience. Lu et al. [105] examined SLM-fabricated $Co_{29}Cr_9W_3Cu$ porous scaffolds with varying geometries of unit cells (octahedron, face-centered cubic, and hexahedron) to balance mechanical properties and biological performance. Scaffolds achieved values of compressive stress of 3.7–467 MPa, elastic moduli of 2.6–36.3 GPa, and 65% porosity. In vitro and in vivo studies confirmed biocompatibility and osteointegration, with octahedron scaffolds demonstrating superior mineralisation of bones due to their adaptive mechanical properties. This work underscores the potential of hierarchical scaffold designs with multi-scale features and incorporation of bioactive materials to enhance osseointegration and tissue integration in biomedical applications, offering valuable strategies for hierarchical HCs.

The primary advantage of hierarchical HCs is their good strength-to-weight ratio. Additive manufacturing allows the fabrication of lightweight structures with precise interior geometries, resulting in further weight reduction for parts used in aerospace and other engineering applications [15,26]. Additive manufacturing excels at manufacturing complicated and customised geometries. This capability could be used to customise hierarchical HC designs to fit specific engineering applications, thus enhancing performance and functionality [88,94]. Advances in AM materials, such as high-performance plastics, metals, and composites, enable innovation in hierarchical HC designs. Engineers can explore novel materials with improved mechanical properties for particular uses [88]. Topology optimisation, along with AM, allows the design of highly efficient and structurally optimised hierarchical HCs. This approach involves algorithmically determining the best material distribution within a particular design space, resulting in lightweight and high-performance structures [2,12,88–90,94]. Additive manufacturing offers rapid prototype and iterative design methods. Designers could rapidly iterate and test various hierarchical HC configurations, resulting in shorter development cycles and improved designs [82,88]. Hierarchical HCs are typically used to incorporate multiple features into a single component. This includes adding functionality such as fluid flow channels, electrical conduits, and even embedding sensors to the printed parts, which expands their use [12,15,88,106]. Additive manufacturing is intrinsically more material-efficient than traditional production methods [82,94]. The capacity to build complicated structures, layer by layer, reduces material waste, which aligns with sustainability objectives [66].

Advanced AM technologies, including SLM, electron beam melting (EBM), and binder jetting (BJ), are often adopted and show significant promise for fabricating complex geometries like hierarchical HCs. The following discussion compares the capabilities and limitations of these three mentioned AM techniques, including their precision, material properties, and challenges, and proposes solutions from the available literature.

5.1 Comparison of selected additive manufacturing technologies

5.1.1 Selective laser melting (SLM)

SLM is extensively used for manufacturing metallic hierarchical structures due to its high precision and capability to produce near full-density structures. The technology allows for layer thicknesses as small as 20–50 μm, facilitating the fabrication of fine features necessary for achieving multiple hierarchy levels in scaffolds. However, the rapid cooling rates inherent to SLM can induce thermal residual stresses, microstructural anisotropy, and porosity (typically around 1–5%). These factors can adversely affect the fatigue performance and mechanical reliability of the structures, especially under cyclic loading scenarios [83,92,107–110].

5.1.2 Electron beam melting (EBM)

EBM uses an electron beam to fuse powder on a powder bed within a vacuum, effectively minimising risks of oxidation during processing. The higher build temperatures characteristic of EBM help to mitigate thermal residual stresses, resulting in more uniform and refined microstructures compared to SLM. However, the process's coarser resolution, with layer thicknesses ranging from 50 to 100 μm, limits its capability to produce intricate hierarchical features. Additionally, EBM-fabricated structures often exhibit porosities in the range of 2–8%, necessitating post-processing to achieve desired mechanical and biological performance standards [111,112].

5.1.3 Binder jetting (BJ)

BJ employs a liquid binder to selectively bind powder particles layer by layer, followed by a post-processing sintering step. This technique provides precise control over porosity, facilitating the production of scaffolds with customised permeability, particularly suitable for biological applications. However, materials fabricated via BJ typically exhibit lower mechanical strength, attributed to incomplete sintering and the absence of solid-state phase transformations. Layer thicknesses in BJ generally range between 50 and 200 μm, with dimensional tolerances influenced by sintering parameters and the properties of the feedstock powder [113–115].

Table 1 provides a comparative analysis of SLM, EBM, and BJ techniques based on critical parameters such as layer thickness, porosity levels, material anisotropy, resolution of features, and fatigue life. Understanding these distinctions is crucial for selecting the appropriate AM technique to meet the design requirements for the specific hierarchical structure.

High cooling rates in SLM induce thermal gradients, causing warping and microcracks, mitigated by preheating the build platform and optimising scanning strategies such as rotating laser paths. In contrast and as mentioned previously, EBM's elevated build temperatures inherently minimise these stresses. The reuse of powder in SLM and EBM comes with risks of the oxidation of particles, changes of morphology, and contamination. However, controlled

Table 1. Comparison of SLM, EBM, and BJ in terms of key parameters relevant to hierarchical structure fabrication.

Parameter	SLM	EBM	Binder Jetting (BJ)
Layer thickness	20–50 μm	50–100 μm	50–200 μm
Porosity levels	1–5%	2–8%	10–20% (adjustable)
Material anisotropy	High	Low	Moderate (depends on sintering)
Resolution of features	High (fine details)	Moderate	Low (requires post-processing)
Fatigue life qualitative)	Moderate	High	Low

sieving and printing environments of inert gases and only for EBM help maintain quality for the consistent performance of parts. Post-processing, such as heat treatment, surface polishing, and hot isostatic pressing (HIP), address the problem of porosity and anisotropy across AM methods but increase cost and production time. In BJ, post-sintering is essential to achieve adequate mechanical properties. The choice of AM technology for hierarchical structures (HCs) depends on specific requirements, such as mechanical performance, biocompatibility, and cost. Exceptional precision of offered by SLM, EBM ensures superior microstructural integrity, and BJ enables customised porosity for biological applications. Overcoming challenges of thermal residual stresses, recycling of powder, and post-processing is critical to fully leveraging these technologies.

In its entirety, addressing the challenges of hierarchical HC design for AM requires a multidisciplinary approach that includes materials research, engineering, and process optimisation. As technology advances, the combination of hierarchical HC design and 3D printing shows immense promise for manufacturing lightweight, high-performance structures in numerous engineering industries. To further explore the potential of hierarchical HCs in advanced engineering applications, future studies must focus on addressing the current challenges while leveraging the evolving capabilities of AM, particularly for high-stakes sectors such as aerospace.

6 Future studies and advances of designing hierarchical honeycombs applied to aerospace sectors

The design and fabrication of hierarchical HCs for aeronautical applications is an active topic of research, with scientists and engineers looking into new alternatives and advances to improve their properties and applications [95,106,116–119]. Following are some prospective areas for future aerospace research and development with hierarchical HCs.

- Investigating and developing novel materials with improved mechanical properties, thermal stability, and ones that are lightweight in design [120]. This includes researching improved composites, nanomaterials, and novel metal alloys that are suited for hierarchical HCs.

  Example of methodology. Employ high-throughput screening and computational modelling to identify materials with optimised characteristics, using material informatics to evaluate composites and nanomaterials for hierarchical HCs.

  Example of materials and technology. Investigate AM-compatible metal matrix composites such as Ti-based composites with ceramic reinforcements and high-entropy alloys for enhanced performance. Integrate nanotechnology to design nanostructured materials with precise thermal and mechanical properties.
- Investigating AM methods that allow the use of multiple materials in a single print [12]. This could entail the incorporation of various materials within the hierarchical HC to improve specific characteristics or introduce functional features.

  Example of methodology. Develop hybrid AM systems combining direct energy deposition (DED) and material extrusion to achieve seamless multi-material transitions, utilising voxel-based allocation of materials for precise placement within hierarchical HCs.
  Example of materials and technology. Employ multi-material stereolithography or binder jetting to integrate functional materials, such as conductive polymers, for enhanced mechanical and functional characteristics.
- Constructing hierarchical HCs that have higher structural efficiency and robustness by mimicking biological structures such as bone or plant tissues [121]. Mimicking nature's designs could lead to new aerospace solutions.
  Example of methodology. Use bio-inspired design frameworks to mimic natural cellular structures like trabecular bone-inspired Voronoi patterns and plant xylem-based fractal geometries. Optimise designs for the distribution of stress and resistance to deformation using FEA.
  Example of technology. Combine biofabrication techniques with additive manufacturing to replicate complex biological microarchitectures.
- Additionally, investigating the use of functionally graded materials (FGMs) in hierarchical HCs [15]. This involves tailoring material properties within the structure to improve structural performance under different loading conditions, resulting in improved structural integrity and adaptability.
  Example of methodology. Develop gradient design algorithms that determine optimal distribution of properties within a hierarchical HC. Use molecular dynamics and phase-field modelling to predict interfacial behaviours in FGMs.
  Example of technology. Leverage laser-based AM techniques like SLM or direct metal laser sintering (DMLS) to achieve controlled material gradients.

– Using machine learning methods and optimisation approaches to build and customise hierarchical HC architectures [122]. These methods could assist in determining optimal shapes and material distributions for specific aerospace applications, whilst simultaneously considering the constraints of complex designs.
Example of methodology. Use generative design and reinforcement learning techniques to optimise hierarchical HC architectures for specific loading scenarios. Use neural networks to analyse and predict performance metrics based on historical data.
Example of technology. Integrate AI-driven design platforms like Autodesk Fusion 360's generative design tool with advanced modelling software such as ABAQUS, ANSYS, COMSOL Multiphysics, Altair HyperWorks, MATLAB and Simulink for iterative improvements.
– Integration of smart materials and embedded sensors into hierarchical HC designs [121,122]. This could enable real-time structural health monitoring, giving vital data for predictive maintenance while also improving the overall safety and reliability of aircraft parts.
Example of methodology. Use integrated circuit printing techniques to embed sensors and actuators within the hierarchical HC design. Investigate piezoelectric or shape-memory alloys for dynamic response capabilities.
Example of technology. Incorporate inkjet-printed conductive materials for sensor networks, enabling real-time data acquisition for structural health monitoring.
– Keeping up with the latest breakthroughs in AM technology. This includes faster printing speeds, higher resolution, and the ability to print a wider range of materials using multiple lasers [12]. Advances in 3D printing could allow for more efficient and cost-effective manufacture of hierarchical HCs.
Example of methodology. Invest in research on high-speed, high-resolution printing techniques. Develop scalable AM systems using synchronised multi-laser setups to improve production efficiency.
Example of technology. Employ advanced AM systems like continuous liquid interface production (CLIP) for rapid prototyping and electron beam melting (EBM) for high-strength material fabrication.
– Continuing to improve and apply topology and shape optimisation algorithms to hierarchical HC designs [123]. This involves using computational methods to optimise material distribution within a particular design region, resulting in structures that are more lightweight and efficient.
Example of methodology. Use advanced algorithms like level-set methods and metaheuristic approaches for the optimisation of the distribution of materials. Integrate topology optimisation with machine learning for real-time feedback during the design process.
Example of technology. Implement software like ANSYS or Altair Inspire to execute optimisation routines with high computational efficiency.
– Encouraging collaboration among materials scientists, aeronautical engineers, and experts in other relevant fields. A multidisciplinary approach might improve innovation by merging knowledge of materials, manufacturing processes, and aircraft design.
Example of Methodology. Establish collaborative platforms and shared databases to integrate knowledge across disciplines. Organize innovation hubs for joint projects between industry and academia.
Example of technology. Use collaborative tools like cloud-based design software for real-time co-development.
– Conducting full life cycle evaluations to determine the environmental impact of hierarchical HC materials and manufacturing processes [124,125]. This includes aspects such as energy usage, waste generation, and recyclability.
Example of Methodology. Apply life cycle assessment (LCA) methodologies to evaluate energy inputs, emissions, and generation of waste across all manufacturing stages. Develop databases for benchmarking environmental performance.
Example of technology. Use software tools like SimaPro or GaBi for comprehensive LCA.
– Working towards developing industrial standards and certification procedures for hierarchical HC materials and structures. This is critical for widespread adoption in aircraft applications, assuring safety and regulatory compliance. Ongoing research and development in these areas are expected to improve hierarchical HCs, rendering them easier to customise, efficient, and useful to a wider range of aeronautical applications.

Example of methodology. Collaborate with standardisation bodies such as ASTM, and ISO to develop guidelines tailored to hierarchical HCs. Pilot certification processes using prototype testing under real-world conditions.
Examples of technology. Use digital twins for modelling compliance with regulatory standards, enabling early detection of potential issues.

By leveraging these detailed methodologies and technologies, the proposed research areas can be effectively advanced, fostering innovation and enabling the broader application of hierarchical HCs in aeronautical engineering.

7 Conclusion

– The multiscale design, load transfer mechanisms, anisotropic properties, scale dependency, energy absorption capabilities, and fracture behaviour of hierarchical HCs all affect their deformation behaviour. By thoroughly understanding and characterising all of these factors, it is anticipated that engineers could generate hierarchical HCs with particular mechanical properties for a range of engineering applications, including energy-absorbing structures, lightweight structures, and materials that are capable of withstanding high- impacts load.
– When determining the possible levels of hierarchy that can be achieved for hierarchical HCs, material properties used in production of the parts, constraints in using

imaging tools for evaluation of parts, generating accurate numerical models to validate experimental data, prematurely developed algorithms for controlling complex hierarchical data sets, heterogeneity observed in biological materials being mimicked, scaling of parts, and manufacturing defects, are all primary challenges in design for AM.
– The specific characteristics and properties of the hierarchical honeycomb structures are determined by the configurations used. This means that hierarchical HCs can be tailored to specific aerospace applications.
– Considering the challenges of hierarchical HC design for AM requires a multidisciplinary approach that involves materials research, engineering, and process optimisation. With expected advances in technology, the combination of hierarchical honeycomb design and AM has great potential for manufacturing lightweight, high-performance structures in a wide range of aerospace industries.
– Ongoing analytical, numerical, and experimental modelling studies in these areas are projected to improve hierarchical HCs, resulting in them being more customisable, efficient, and applicable to a broader range of aeronautical applications.

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Conflicts of 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.

Data availability statement

The raw/processed data required to reproduce these findings can be shared on request.

Author contribution statement

The authors contributed as follows: Conceptualization, M.I.C.; Methodology, M.I.C.; Data Validation, M.I.C., T.C.D., M.M., and A.M.; Formal Analysis, M.I.C., T.C.D., M.M., and A.M.; Investigation, M.I.C.; Data Curation, M.I.C.; Writing – Original Draft Preparation, M.I.C.; Writing – Review Editing, M.I.C., T.C.D., M.M., and A.M.; Visualization, M.I.C., T.C.D., M.M., and A.M.; Supervision, T.C.D., M.M., and A.M.; Project Administration, T.C.D., and M.M.; Funding Acquisition, T.C.D., and M.M.

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