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Advanced Multifunctional Composite Cellular Structures: Innovations and Impact in Aerospace Engineering

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Abstract

In recent years, the aerospace industry has increasingly adopted composite materials and honeycomb structures to address the need for lightweight, high-performance, and energy-efficient designs. These advancements have led to the replacement of traditional metallic components with fiber-reinforced polymers, ceramic matrix composites, and advanced honeycomb cores in critical structural parts such as wings, fuselage skins, and rotor blades. Honeycomb sandwich panel structures, due to their superior specific stiffness and energy absorption capabilities, are widely used in both civilian and military aircraft. This paper investigates the mechanical performance, design applications, and manufacturing techniques of these structures. Special attention is given to the integration of gradient-density honeycomb cores, radar-absorbing materials, and morphing wing technologies that enhance aerodynamic efficiency and stealth capabilities. The study also addresses prevalent challenges such as impact resistance, lightning strike vulnerability, flutter phenomena, and water ingress, which can compromise structural integrity. Furthermore, the paper explores recent innovations in additive manufacturing and bioinspired designs that support the development of complex geometries and adaptive structures. This article is prepared as a comprehensive review, aiming to synthesize and critically evaluate recent advances in composite materials and multifunctional cellular structures in aerospace engineering.

Keywords: Honeycomb; Composite structure; Aerodynamic efficiency; Sandwich panel; Fiber-reinforced polymers

1. INTRODUCTION

Throughout history, humans have endeavored to employ a variety of methods to maximize benefit while minimizing cost. Two such approaches were harnessing the forces of nature and reducing the mass of objects. Wind power, for instance, has a long record of application—from sailboats and windmills to modern wind turbines and gliders. These two principles, which have long been pursued by humankind, remain among the most fundamental in various industries, particularly aerospace and aviation. Over time, aerospace structures have undergone continuous development and evolution with the primary objective of enhancing their efficiency. Windmills, in particular, played a pivotal role in the early development of the energy industry, forming the basis for today's wind turbines. As technology advanced, engineers sought to design turbines that were not only larger but also lighter, thereby significantly improving their efficiency.

A similar phenomenon has been observed in the aviation industry. Initially, the majority of the fundamental components of aircraft, including airplanes and helicopters, were composed of metals. This material choice led to several drawbacks, including an increase in weight, a reduction in cargo carrying capacity, elevated fuel consumption, and a diminished flight range. Advancements in the industry and the body of knowledge concerning materials have led to the gradual replacement of metal components with composite materials, such as glass and carbon fibers, and ceramic fibers, in order to enhance the efficiency and performance of the industry. The objective of this research is to examine the materials and parts that have been replaced and to identify new materials and parts for future research and development.

The advent of composite parts in all industries has led to a reduction in manufacturing costs, with these parts now able to be manufactured using more straightforward methods. A comparison of the mechanical properties of

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the original metal parts and their composite replacements reveals a significant decrease in mass and volume. The advent of engineering innovations has led to the development of lightweight yet robust structures, exemplified by honeycomb structures, which have emerged as a result of these advancements.

The necessity to enhance aircraft design technology is becoming increasingly apparent, particularly in regard to performance, constraints, and sustainability. It is imperative to acknowledge the pivotal role these elements play in propelling advancements in the domains of commercial aircraft and unmanned aerial vehicles (UAVs) [1]. The aim of this review is to provide a comprehensive overview of the state-of-the-art in composite and cellular structures in aerospace engineering, highlighting their advantages, current challenges, and future research directions. Particular emphasis is given to multifunctional design, structural optimization, and novel manufacturing techniques such as additive manufacturing.

2. COMPOSITE MATERIALS AND FIBERS

The future direction of aircraft production is poised to be heavily impacted by the use of composite materials. The development of this technology has accelerated in recent decades, as evidenced by the increasing prevalence of aircraft manufactured in recent years that incorporate high concentrations of fiber-reinforced plastics and light core materials [2].

The utilization of composite materials in aircraft engineering is a well-established practice, with a primary objective being the reduction of the aircraft's overall mass. Typically, these materials are composed of carbon or fiberglass. The properties of this material offer two distinct advantages. Firstly, its mass is reduced, and secondly, the sequential stacking and orientation of its layers can result in a designed strength that can withstand the expected loads [1].

The integration of composite materials into aircraft manufacturing has led to substantial advancements in the aviation industry. Such materials, particularly utilized in structural components such as wings, exhibit superior strength-to-weight ratios, enhanced resistance to corrosion, and augmented design flexibility [3].

The primary benefits of composites over metal components are as follows:

• A high strength-to-weight ratio: Carbon fiber has a mass density of approximately 24% that of steel and 70% that of aluminium.

• A proven durability with reduced maintenance costs and long-term stability.

• New design possibilities: A composite component can replace an entire metal assembly. In the aerospace industry, the most common composite materials used are carbon fiber, glass fiber, and aramid fiber reinforced epoxy. These materials can be engineered to obtain the desired mechanical properties. The matrix utilized for composite materials is high-performance epoxy resin; however, there are also alternative options that can be employed, including phenolics, polyesters, and polyamides [2].

Aerospace composite structures are renowned for their exceptional mechanical properties combined with their low density. However, these composites are prone to failure due to the inherent brittleness of the resin matrix. The response of these materials to impact loading at different energy levels (high- and low-velocity impacts), constitutes a significant area of concern. It is noteworthy that delamination (layer separation) and back-face failure are two distinct types of damage that have been observed to occur following high- and low-energy impacts [4].

The advent of lightweight, flexible materials has engendered a proliferation of innovative designs for wings and tails. The materials utilized in this process include plasticized copoly-amide thermoplastic elastomer (PCTPE), thermoplastic polyurethane (TPU), acrylonitrile butadiene styrene (ABS), balsa wood, carbon fiber composites, and fiberglass [5].

While unrecycled carbon fiber-reinforced polymers (CFRP) exhibit higher fatigue strength than conventional metallic materials, the complexity arises from the separation of stiffeners during post-buckling. The stiffened panels are subjected to repeated compression cycles. The decoupling of diffusion during post-buckling results in stiffened panels being sized to not buckle below their ultimate loads [6].

Ceramic matrix composites (CMCs) (Figure 1) are of particular significance in the aerospace industry due to their lightweight nature. The materials exhibit elevated levels of specific hardness and toughness, in addition to demonstrating remarkable resistance to high-temperature conditions. Research activities related to the study of CMCs and their materials have been progressing towards microscopic and microscale levels. The research methodologies have evolved from macroscopic, similar, and homogeneous theoretical frameworks to more sophisticated multiscale models. Such sophisticated analyses necessitate high-performance parameters of the CMC materials as preliminary requisite data. Research findings have indicated that the microscopic anisotropic elastic properties of CMCs differ from those of the materials used to manufacture them. Research has demonstrated the efficacy of silicon carbide-based CMCs in a range of high-temperature aerospace applications, particularly in the context of engine components. The predominant methodologies employed for the fabrication of silicon carbide-based CMCs encompass chemical vapor deposition (CVD) and chemical vapor infiltration (CVI). These technologies facilitate the sequential deposition of the precursor material for silicon

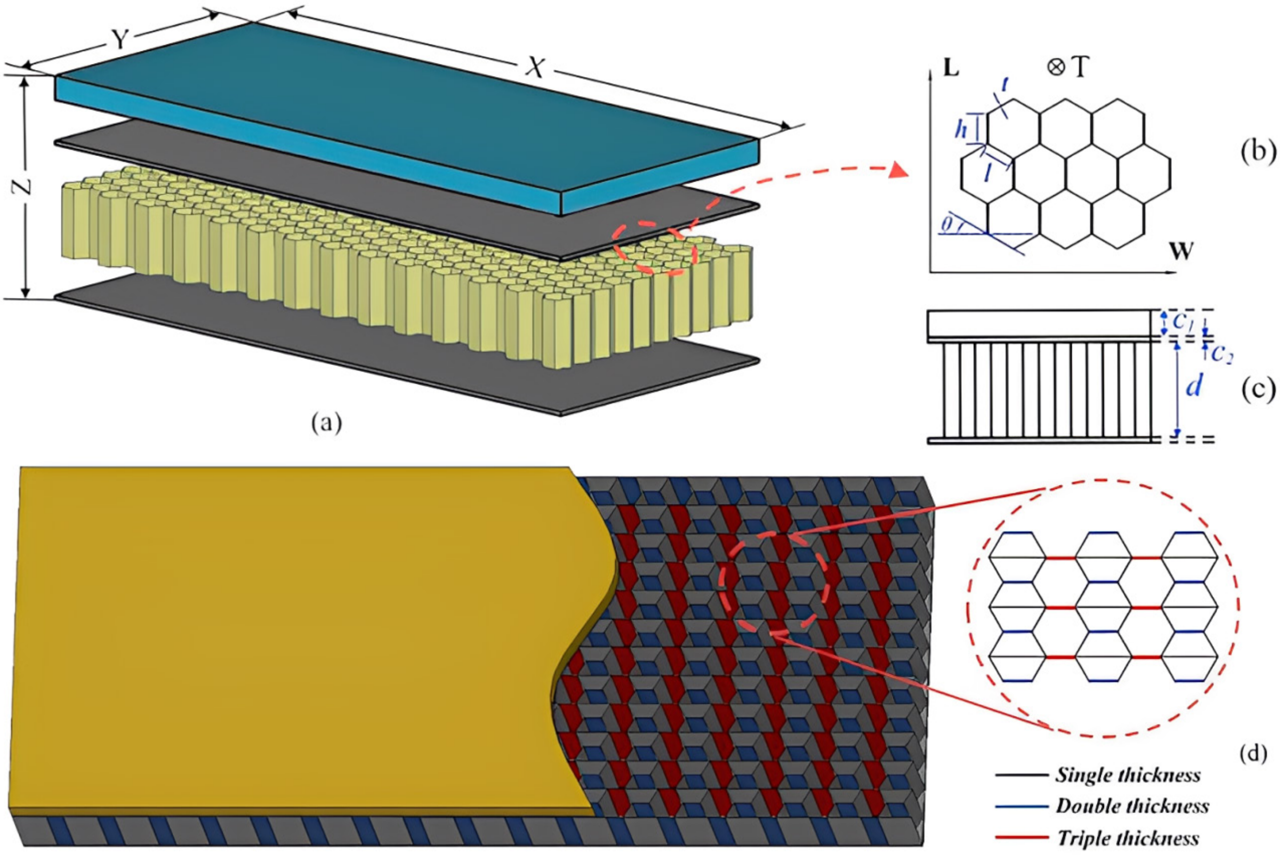

Fig. 1. Structural geometry of ceramic matrix composite (CMC) sandwich systems. (a) General schematic of a CMC sandwich panel, showing ceramic face sheets bonded to a honeycomb core; (b) Hexagonal honeycomb cell geometry, illustrating the periodic unit structure that governs load transfer and energy absorption; (c) Cross-sectional parameters of the honeycomb cell (wall thickness, cell size, and core height) that define the stiffness-to-weight ratio and mechanical performance of the panel; (d) Example of a CMC sandwich reinforced with honeycomb, demonstrating integration of lightweight ceramic layers with a mechanically stable core. Reproduced with permission from Ref. [7], under the terms of CC BY 4.0 license. © 2018 Z. Wang et al.

carbide over the surfaces of the fibers, with controlled pressures and temperatures, thereby creating a matrix of SiC [8].

The utilization of silicon carbide matrix composites reinforced with silicon carbide fibers (SiCf/SiC), CMCs, and nickel-based superalloy GH4169 is of paramount importance for high-temperature applications due to their advanced thermal properties. Silicon carbide (SiC) and SiC composite materials have a wide range of applications in the manufacturing of outer turbine rings. These materials exhibit exceptional resistance to both abrasive wear and the dynamic forces exerted by turbine blades, ensuring their durability in critical aerospace environments. Such high-speed friction action has been observed in both jet engines and steam turbines [9].

In order to further enhance the capabilities of SiCf/SiC composites, the development of commercial prepreg–melt infiltration (MI) and CVI–slurry melt infiltration SiCf/SiC composites have been undertaken, achieving a temperature capability of 1316 °C. Research and development efforts are currently underway to enhance the temperature capability of SiCf/SiC composites to 1755 °C [10].

The epoxy resin exhibits outstanding mechanical properties, remarkable environmental durability, significant toughness, and ease of processing. In contrast, the phenolic resin is characterized by superior fire resistance, commendable temperature stability, minimal smoke and toxic emissions, quick curing times, and cost-effective processing. Furthermore, fiber-reinforced polymer (FRP) composite sandwich structures present a greater geometric complexity than monolithic constructions. Consequently, the design and optimization techniques for FRP composite sandwich structures are considerably more intricate when compared to those for homogeneous monolithic structures [11].

Epoxy resin is a particularly prevalent matrix material among polymer matrices due to its favourable mechanical properties and durability. The utilization of carbon fiber/phenolic and carbon–carbon composites is recommended for nozzles, including exit cones and throat elements, due to their exceptional specific mechanical properties and high thermal resistance. Carbon–carbon composites have demonstrated their efficacy in high-temperature and ablative conditions. The properties of carbon–carbon composites include low thermal expansion, good thermal conductivity, high heat capacity, and wear resistance [12].

Thermoplastics that exhibit significant resistance to fire, smoke, and toxicity (FST), along with durability and ease of fabrication, such as polyetherimide (PEI), polyphenylene sulfide, and poly-ether-ether-ketone (PEEK), are gaining attention for their potential use in aircraft interiors. Ultem™ 9085, a thermoplastic blend of PEI and PEEK, has been synthesized through injection molding and has been effectively utilized in fused deposition modelling (FDM) technologies. This blend is noted for its high resistance to chemicals and thermal conditions, as well as its flame-retardant properties and minimal smoke emission, enabling it to meet most fire safety regulation tests. An additional benefit of Ultem™ 9085 is its exceptional dimensional stability and strength at elevated temperatures. Due to their superior physical properties that align with aircraft regulations, Ultem resins are widely used in applications related to aircraft interiors. At present, the processing of Ultem™ resins is conducted using the FDM technique [13].

Composite materials are specifically engineered based on their intended use and the physical, mechanical, and chemical conditions they will encounter. In structural applications, the arrangement of panels or sandwich composites is particularly notable due to their resistance to compression and bending forces [14].

3. HONEYCOMB COMPOSITES

The mass of an aircraft is a critical performance indicator. Honeycomb sandwich structures represent the most prevalent configuration in the field of aircraft engineering. The selection of a sandwich core, characterized by an optimal balance of stiffness and strength, is of paramount importance. In this regard, the regular face folded core (RFC) emerges as a particularly noteworthy option, offering significant potential for enhancing aircraft performance. RFCs, composed of identical repeating cells, exhibit the capacity for extension along a plane [15].

It is well established that honeycomb sandwich composite structures are prone to damage. A reduction in load-bearing capacity, as well as an overall threat to safety, is the consequence of low-energy impact on the structure. Honeycomb sandwich composites exhibit a unique combination of lightweight and high-strength properties. They possess exceptional specific strength and stiffness. These characteristics render them highly suitable for a wide range of applications within the aerospace industry. These applications include components such as rudders, flaps, elevators, wings/trailing edges, landing gear compartment doors, auxiliary power unit (APU) compartment doors, and radar covers, among others. A typical honeycomb sandwich composite consists of a top panel, a bottom panel, and a honeycomb core sandwiched between them. The use of adhesive film facilitates the adhesion of these components. The top and bottom panels are principally responsible for the overall strength and stiffness of the structure. Conversely, the honeycomb core endures shear loads, preserves the separation between the two panels, and enhances the overall structure's impact resistance, blast resistance, and energy absorption capability. The upper and lower panels of the honeycomb sandwich composite structure are made of fiber-reinforced unidirectional strips. The strips are arranged in a [45/0/90/–45]s stacking sequence (Figure 2) [16].

However, honeycomb sandwich composite structures are vulnerable to lightning damage, which endangers the

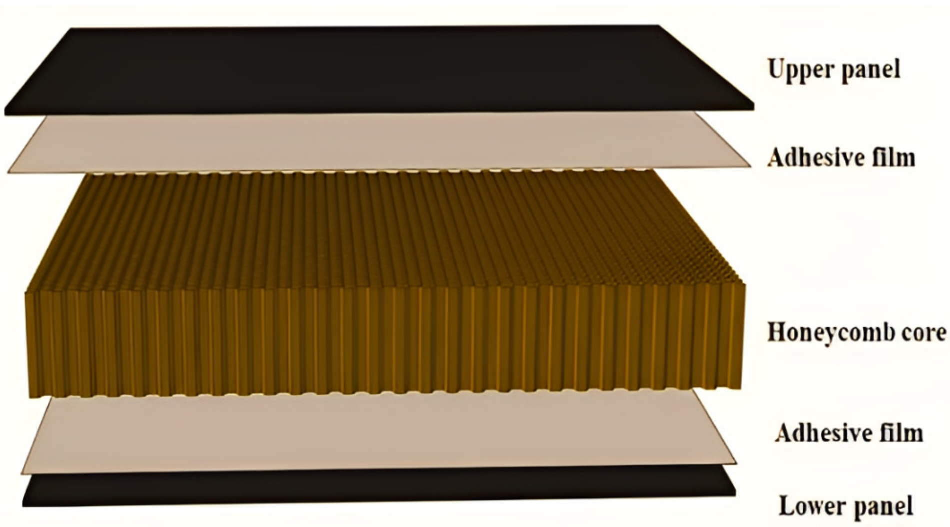

Fig. 2. Honeycomb sandwich composite structure with fiber-reinforced face sheets. The upper and lower panels are composed of fiber-reinforced unidirectional strips arranged in [45/0/90/–45]s stacking sequence, while the central core consists of a hexagonal honeycomb. Adapted from Ref. [16], under the terms of CC BY-NC 4.0 license. © 2023 X. Zheng et al.

structural integrity. Consequently, a comprehensive evaluation of the residual mechanical properties of honeycomb sandwich composite structures following lightning strike is imperative [17].

The mounting demand for stealth technology in military and aerospace applications has precipitated the development of advanced radar-absorbing structures, with particular emphasis on honeycomb absorbing structures (HASs). HASs are recognized as viable substitutes due to their distinctive characteristics. The utilization of radar-absorbing materials (RAMs) has been demonstrated to markedly diminish the extent of radar reflection from targets. The capacity to capture incoming electromagnetic (EM) waves and dissipate energy into various forms, including thermal energy within the material, is exhibited by these materials. The classification of RAMs is typically divided into two primary categories: surface coating materials and structural absorbing materials. The latter combine both radar absorption properties along with mechanical properties, rendering them viable candidates for integration into radar-evading aircraft. Of these, HASs are one of the common types of structural RAMs. The hexagonal honeycomb, in its capacity as an intrinsic structure, has proven to be an effective three-dimensional periodic structural absorbing material. It is characterized by a large absorption frequency range, in conjunction with a high stiffness-to-weight ratio, which renders it adaptable for use as a structural load-bearing unit. Furthermore, it has been observed that modifying the heights of honeycomb can be advantageous in achieving the proposed coating thickness. This observation underscores the significance of meticulous consideration of its structural parameters during the planning stage [18].

Honeycomb, in particular, finds application as an energy absorber due to its unique mechanical properties. A substantial body of research has underscored the significance of honeycomb in enhancing the impact resistance of structural components. Structures such as super hexagonal honeycomb and foam-filled honeycomb panels exhibit higher energy absorption, specific energy absorption capacity, and volumetric energy absorption capacity compared to traditional designs, indicating an improvement in impact resistance and efficiency. Metallic foams have also seen an increase in utilization as energy absorbers, a development attributable to their low density and energy absorption capacity. In general, metal foams are created using a variety of metals, including aluminum, magnesium, iron, titanium, nickel, and copper, as well as their alloys. These foams can be designed to have either closed or open-cell structures, which leads to a range of applications, depending on the density of the structure. The incorporation of metal foams into various structures, such as pipes, sandwiches, or more complex systems, has the potential to enhance energy absorption capacity, deformation modes, and force reduction effects [19].

A considerable number of applications of honeycomb cores in functional sandwich structures, including acoustic liners, necessitate a curved shape, particularly in the case of the inlet geometry of a jet engine. However, the manufacturing process of sandwich cores typically involves first producing them in a flat state and subsequently shaping them into the desired form. This process has the potential to inflict damage to the composite, lead to impaired performance, and result in alterations to cell geometry. In addition to the geometry, a range of materials are under consideration for the different possible configurations of sandwitch structures. For example, in the case of acoustic liners, the core is typically made of aramid paper (Nomex), while the face and back plates are constructed from carbon fiber- and glass fiber-reinforced epoxy resin [20].

The variation in relative density along the honeycomb structure, achieved by implementing a gradient honeycomb and deliberately positioning high-density layers at the impact end and low-density layers at the end far from the impact, has been demonstrated to markedly enhance the energy absorption capacity of the honeycomb structure. In addition to the aforementioned points, this approach has been demonstrated to result in a substantial reduction in forces, even at the outlet end. In this context, the present study proposes an innovative topological structure of an hourglass-shaped honeycomb by converting the conventional circular honeycomb, thus leading to honeycombs by way of interconnected and reciprocal voids. Additionally, a salient issue pertaining to the functionality of sandwich panels pertains to their dynamic response to external impacts emanating from diverse sources, including fallen tools, hail, and aircraft crashes. Such an impact has the potential to induce partial or complete failure of the material. Compressive deformation occurring within the circular honeycomb sandwich panel at the lower end is an outcome that initiates the formation of wrinkles, which inevitably leads to a loss of structural integrity. This phenomenon can be attributed to the sudden propagation of stress waves towards the lower end during scenarios of low-speed impact, thereby leading to the concentration of the contact force at the aforementioned location [21].

Most UAV honeycomb sandwich body structures consist of two layers of carbon fiber (or 7075 aluminum skin) and a single layer of Nomex honeycomb core. When faced with damaging elements such as shock waves and high-speed fragments, the energy absorption capacity of the core layer is relatively limited, and the longitudinal tensile properties of the skin are not adequately demonstrated. An impact velocity of 10 m/s can entirely compromise the structure, indicating that its impact resistance is insufficient, primarily catering to lightweight requirements. Consequently, research on honeycomb sandwich structures should prioritize understanding the failure modes and energy absorption post-failure to mitigate the overall structural damage. Although the honeycomb sandwich structure, which includes a Nomex honeycomb core and carbon fiber skin, effectively reduces the fuselage weight, it is insufficient to withstand fragment impacts. Currently, there is a scarcity of reported research on the structural design of UAV honeycomb sandwich bodies. Therefore, to achieve air superiority, it is crucial to design a new honeycomb sandwich body structure that is comprehensive, effective, and resistant to impacts. The conventional honeycomb structure is typically characterized by regular shapes, including quadrilateral, hexagonal, circular, foam, and corrugated forms. Building upon the traditional honeycomb sandwich structure, innovative designs such as chirality and anti-chirality have emerged, along with structural composites, stepped, and mixed honeycomb sandwich structures utilizing various materials [22].

Recent research on convective cooling channels has emphasized the importance of enhancing both heat dissipation efficiency and structural load-bearing capacity. In this context, natural honeycomb architectures have been widely regarded as promising bioinspired models due to their outstanding mechanical properties and their ability to stabilize temperature ranges between 25 and 45 °C under varying environmental conditions. However, most investigations have predominantly focused on the macroscopic features of honeycombs, while the biomimetic potential of their microstructural organization has been comparatively underexplored. For example, Li et al. [23] conducted a comprehensive analysis of natural honeycombs across multiple length scales using advanced techniques such as environmental scanning electron microscopy and atomic force microscopy, thereby providing valuable insight into the layered composite morphology formed by beeswax and bee silk. Their work also demonstrated how anisotropy and temperature regulation can be explained through experimental testing and numerical simulations, which in turn supported the development of novel porous materials incorporating surface composite coatings [23].

To enhance the classification of cellular structures, these structures have been categorized into three distinct types: foams (which include both open-cell and closed-cell varieties), honeycombs, and lattice structures. The unit cells within foam structures are generated randomly, and the orientation of the cell walls varies unpredictably in space. Foams represent the most prevalent type of cellular structure, with examples including cork, cancellous bone, and wood, all of which exhibit various foam characteristics. Conversely, honeycomb structures are distinguished by their regular geometry, with unit cells that exhibit uniformity in both shape and size. Honeycombs can feature a variety of cell shapes, including tetrahedrons, triangular prisms, square prisms, hexagonal prisms, and others. Finally, lattice structures are defined by their architectural arrangement, consisting of an array of spatial unit cells that possess edges and faces [24].

4. STRUCTURAL DESIGN

The wing is the primary component of an aircraft responsible for producing lift, thereby playing a vital role in both the aircraft's design and its flight performance. The wing skin, which interacts directly with the airflow, experiences complex aerodynamic loads during flight, potentially leading to fatigue deformation, structural damage, and other associated hazards. Consequently, it is imperative to conduct a stress analysis on the wing skin to ensure the integrity of the overall structure [25].

A number of structural components in aircraft are composed of an isotropic material, specifically 2024-T3 aluminum, which is utilized in the fabrication of the front spar, rear spar, and all ribs. The upper and lower skins are composed of five layers of composite material, specifically carbon fiber. The trend indicates that the overall thickness increases with greater mass, and the critical speed of this trade-off reflects the objective of multi-objective design optimization. While thicker structures may offer enhanced safety, they necessitate higher manufacturing costs [1].

In the case of lightweight inner core structures, such as blades or wings, the primary structures employed are foams (polyurethane, polypropylene, or polyvinyl chloride) or honeycomb/lattice structures, which provide a customized mass distribution throughout the structure. The helicopter's rear rotor blade is composed of a sandwich composite that is covered with aluminum sheet. The primary rotor blades are composed of glass fiber-reinforced plastics. In the blade structures, the spar was reinforced with glass materials, and the honeycomb elements were composed of Nomex or glass epoxy. According to Hadăr et al. [2], compared two types of blades, one made of aluminum and the other composed of various composite materials, including glass cloth/epoxy, carbon/epoxy, and Kevlar149. The study demonstrated that carbon/epoxy blades with [0/90] and [–45/45] orientations exhibited superior strength compared to aluminum blades and were capable of withstanding higher loads.

The body panels are composed of thermoplastic composites and metallic materials. Coupon and structural detail testing are a methodical approach employed to ascertain the properties of composite materials. This testing facilitates the evaluation of the formation and propagation of localized damage, as well as the reduction in strength, under static and fatigue loading [26].

Aircraft are engineered to withstand a range of loads. Aerodynamic loads, also referred to as "air loads", are generated by the forces and moments resulting from the dynamic pressure exerted on the aircraft. It is imperative to acknowledge that these loads encompass the lift and drag forces exerted on the wings, in addition to moments such as the wing twisting moment and yaw. In contrast to aerodynamic loads, inertial loads involve forces and moments that act on aircraft structures due to acceleration. An example of such a structure would be a fuel tank or battery, where no aerodynamic loads occur; however, these structures must possess a robust design capable of withstanding forces induced by applied load factors. Operational loads are distinct from aerodynamic forces and inertial forces, which are generated due to regular aircraft functioning. Examples of such operational loads include forces on door hinges, latches, floor loads, and forces due to wing motion, among others [3].

It is evident that avian species possess distinctive flight characteristics that surpass even the most sophisticated drones. This distinction can be attributed to the unique architecture of their lightweight, flexible wings and tails. The advent of 3D printing, servomotors, and composite materials has resulted in a paradigm shift in aircraft design, with novel concepts taking inspiration from avian flight. These innovations have the potential to yield flight characteristics that surpass those of conventional designs. The objective of shaping technology is to enhance the aerodynamic efficiency and power of aircraft by eliminating traditional control surfaces and implementing wings with the capacity to undergo significant deformation [5].

Variable wings have the capacity to spontaneously adjust their shape in different flight missions and under different environmental conditions, thereby maintaining superior aerodynamic performance. This adaptability confers a substantial advantage to variable wings in the management of complex and dynamic flight environments. Research and application in the field of variable wings will not only increase the aerodynamic efficiency of aircraft but may also bring technological advances to the aerospace industry in the future. The incorporation of flexible wings has been demonstrated to be a pivotal factor in the reduction of wing vibration and the delay of airflow separation. These phenomena are of paramount importance in enhancing the overall performance of aircraft [27].

The MataMorph-3 wing and tail stabilizers are fabricated using a combination of hybrid ribs, integrating stiff leading-edge elements that are meticulously designed to support servomotors, with flexible trailing-edge components comprising compliant strips connected to servomotors, enabling rib deformation. A thin, multi-layer, meticulously engineered carbon fiber skin covers the ribs, conforming to the required shape with the help of advanced sliders at the trailing edge. Structural support linkage systems are strategically mounted between ribs to provide support to the skin. A study was conducted to analyze the aerodynamics of camber-forming wings versus conventional airfoils. The objective of the study was to compare the benefits of variable camber wings. The study corroborated greater aerodynamic efficiency, agility, and maneuverability of camber-forming wings with regard to conventional airfoils [28].

The body panel, manufactured by Adamant Composites, consists of a thin, curved skin supported by two stiffeners in its longitudinal direction (floor) and a rigid metal frame along the perimeter. The stiffener elements are connected using various joining methods, including traditional mechanical fastening inside an autoclave. The materials utilized in the fabrication of the panel under review encompass a range of advanced materials and joining concepts. In more precise terms, the skin of the structure consists of a fiber-reinforced plate with a thermoplastic matrix composed of low-melting polyaryl ether ketone (LMPAEK), while the strands are made of a rigid epoxy matrix preform. Furthermore, the frame is composed of an aluminum alloy sheet. The integration of the frame with the skin is facilitated by the implementation of specialized bolts, which are specifically designed for aeronautical applications [26].

The mechanical requirements for this type of sandwich structure are contingent upon the intended application. In aircraft design, one of the critical considerations for the leading edge of wings is the ability to withstand bird strikes, which are common impact events during flight and can cause severe structural damage. Therefore, the suction panel located at the leading edge must demonstrate sufficient strength to resist the impact forces generated by bird collisions, while the suction panel situated at the trailing edge must exhibit resistance to the bending moments resulting from the wing's deformation. This approach integrates the benefits of active suction in the wing, which is distinguished by enhanced efficiency through reduced drag, and a lightweight sandwich structure (Figure 3) [29].

It has been observed that large transport aircraft are often equipped with a wing design that exhibits a high aspect ratio and sweepback angle. It is imperative to consider the necessity of a high lift-to-drag ratio. The utilization of composite materials is typically employed to facilitate the development of lightweight structures. However, this practice can concomitantly engender significant static aeroelastic issues for the aircraft. In the context of supersonic aircraft flight, the aerodynamic load characteristics are notably intricate. The substantial aerodynamic load exerts a significant influence on wing deformation, giving rise to geometric nonlinear effects. These effects, in turn, have a profound impact on the static aerodynamic elasticity characteristics of the wing. In the context of Loads, the elastic deformation of the wing under aerodynamic loads can result in substantial changes to the wing's structure and performance. The forces of lift and drag must be considered. The wings of large aircraft are typically designed with a high aspect ratio configuration, and their fabrication

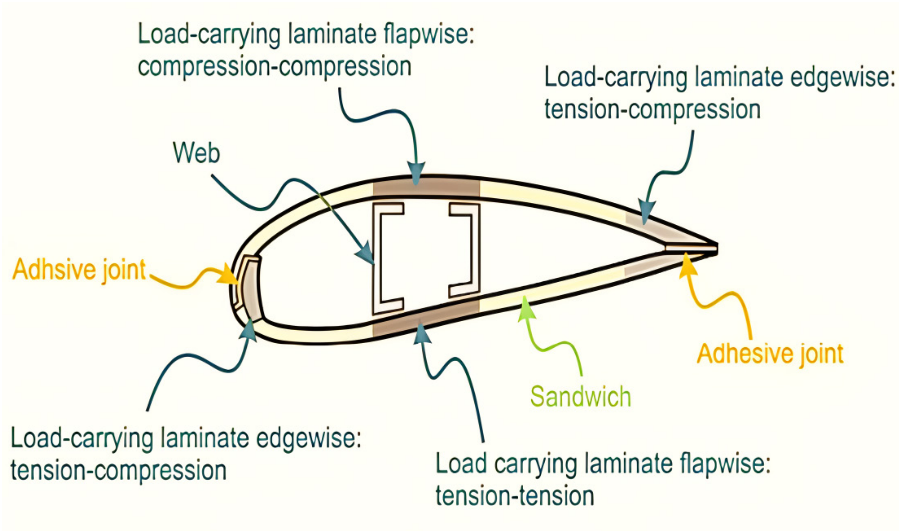

Fig 3. Wind turbine blade airfoil sandwich panel structure. The figure illustrates the key components and load-carrying laminate orientations within the cross-section of the blade. The sandwich panel consists of two outer laminates (flapwise and edgewise) responsible for carrying tension and compression loads, separated by a core ("web"). Adhesive joints are shown connecting the laminates to the web. The flapwise laminate is under compression and tension, while the edgewise laminate carries tension and compression loads. Reproduced from Ref. [30], under the terms of CC BY-SA 4.0 license. © 2017 L. Mishnaevsky et al.

increasingly utilizes composite materials, thereby enhancing the flexibility of the wing and concomitantly compromising its static strength. This phenomenon, known as aeroelasticity, represents a significant challenge in the design and operation of contemporary passenger aircraft. The majority of current passenger aircraft exhibit significant deformation during cruise, leading to discrepancies with the intended frame profile. This deviation leads to a structural alteration in the position of the center of gravity, thereby reducing the limited angle torsional deformation. Gravity exerts a substantial influence on the aerodynamic focus, which shifts toward the front of the aircraft, thereby diminishing the aforementioned deformation [31].

In the context of aircraft engine design, particular attention has been devoted to composite inverted thrust cascades with blades and inclined beams. The structure and operational load characteristics of the cascade were analyzed, and a finite element model incorporating progressive damage analysis was developed. The significance of the thrust reverser as a component of an aircraft engine is of paramount importance. This issue is especially salient in the context of contemporary trends, which are marked by an increase in aircraft speeds and the concomitant extension of landing roll distances. The reverse thrust mechanism plays a crucial role in shortening the landing distance of an aircraft, thereby reducing the reliance on the braking system. Moreover, this mechanism has the potential to enhance the longevity of braking components and optimize the aircraft's capacity to manage contingencies, inclement weather, and operations on confined runways. In the case of a cascade thrust reverser, the cascade itself is the key element that redirects airflow to generate reverse thrust. These reverse thrust cascades are subject to a stringent set of standards that encompass various disciplines, including aerodynamics, acoustics, and structural engineering. These standards address critical parameters such as performance, weight, and reliability. The specifications of the cascade are vital factors influencing the overall effectiveness of the thrust reverser [32].

Aircraft cabin interior panels are produced utilizing a standard sandwich composite configuration, which consists of an aramid honeycomb core that is bonded to outer layers or face sheets, typically made from glass fiber epoxy prepreg. There are three primary manufacturing techniques for sandwich constructions: autoclave, press, and vacuum bag molding. In the case of autoclave or press processing, all components of a sandwich panel undergo curing in a unified process known as co-curing. Conversely, vacuum bag molding requires multiple stages of lay-up and curing. Co-curing refers to the simultaneous curing of the face sheet composite and the adhesive. This study will primarily focus on the co-curing technique in conjunction with the production technology of compression molding [33].

Aircraft doors and hatches are constructed using thick CFRP-honeycomb sandwich panels, necessitating the filling of certain areas with epoxy resins to create a solid point for securing metallic components, a procedure referred to as structural potting. This potting process is generally performed manually, requiring skilled personnel, which results in a bottleneck within both the production workflow and the overall productivity rate. Structural potting fundamentally involves the injection of epoxy resin into honeycomb panels, a task that is highly demanding in terms of manual labor, is time-intensive, and entails the handling of chemicals. The quality of the outcome is indeed significantly influenced by the proficiency of the personnel involved. The automation of potting processes would promptly decrease the duration of the process, minimize material waste, and lower the rate of quality defects. Concurrently, it would enhance repeatability and safety in handling. Also, automation would contribute positively to the overall efficiency of the process [34].

5. MANUFACTURING

In order to adapt to these diverse working conditions, aerospace vehicle designs have been modified to incorporate complex curved aerodynamic lines and a substantial number of composite materials. This shift presents novel challenges for the production and assembly of aerospace vehicles [35].

Among the various manufacturing routes, mold-based fabrication has been widely adopted for composite blades and rotor components. In this process, the skin is the first component inserted into the molds. Prior to the placement of the initial layer of material, a chemical mold release agent was applied to the interior surfaces of the molds. A primary benefit of this approach is that the manufacturing cost of a new blade at full scale is reduced, whereas the price of a new aluminum alloy tail rotor blade from a helicopter manufacturer is approximately four times higher. This cost disparity can be attributed to the necessity of metal blade manufacturing processes, the involvement of multiple suppliers, and the requirement of personnel with distinct certifications, all of which contribute to the overall expense. Additionally, the assembly of composite components by hand can be efficiently organized within a relatively compact warehouse space, thus minimizing the need for extensive machinery [2].

Fused deposition modeling (FDM) is a form of 3D printing that involves the extrusion of material to create a three-dimensional object. A material is liquefied via a nozzle, resulting in the extrusion of filament into an existing structure. The majority of contemporary methodologies employed for the fabrication of carbon fiber components utilize molds, wherein both sheets of carbon fiber are positioned on the mold in layers or by means of adhesive tape using industrial robots. While these methods can yield satisfactory mechanical properties, they are often incapable of addressing highly curved parts or complex geometries, where issues such as buckling or tearing have been observed. The employment of FDM facilitates the directed placement of individual, pre-impregnated filament lines, thereby obviating the necessity for costly molds and enabling the fabrication of more intricate components with elevated curvatures. The concept of using FDM-based molds for the manufacture of CFRPs was proposed in

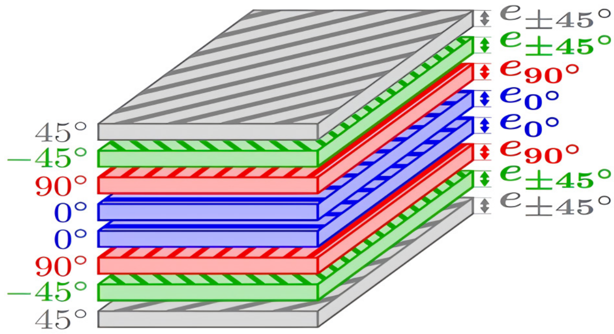

Fig. 4. Layup configuration of composite laminates for buckling resistance. The parameter *e* denotes the laminate thickness. Strategic positioning of 0°, 90°, and ±45° plies enhances the buckling resistance of the structure. Reproduced from Ref. [37], under the terms of CC BY-NC 4.0 license. © 2025 S. de Longueville et al.

eliminating the need for a separately built mold, reducing the cost and time needed for the production of CFRP parts [36].

The layup configuration is designed to increase the membrane stiffness of the laminate and/or to increase the buckling resistance at the specified critical buckling load according to a specified thickness distribution of individual plies. The 0° and 90° inner plies are strategically positioned to optimize the overall membrane stiffness of the layup. The 45° and –45° plies are strategically positioned in the outermost layers of the layup, maintaining a substantial distance from the symmetry plane. This approach is intended to optimize their capacity to enhance the structural buckling resistance (Figure 4) [37].

The process of additive manufacturing gyroid specimens has been shown to possess both advantages and disadvantages. A notable benefit is the capacity to engineer intricate geometries, a capability that is crucial for numerous applications. Furthermore, the print quality is attained through the utilization of reduced layer thicknesses, leading to isotropic behavior. However, a notable disadvantage associated with the implementation of stereolithography (SLA) and selective laser sintering (SLS) technologies is the necessity of removing residual material. The liquid resin that is incorporated into the structure following the printing process is capable of being partially removed through washing; however, the solvent movement is typically inadequate to access all internal components of the structure. The process of removing residual powder from the internal structure is more challenging due to the necessity of mechanical intervention [29].

The rapid development of 3D printing technology has rendered the expeditious fabrication of complex components through additive manufacturing a tangible prospect. A variety of 3D negative Poisson's ratio (NPR) honeycomb superstructures have been developed and constructed by scholars. These superstructures are the result of the suitable organization of 2D lattices, and include 3D chiral, 3D re-entrant, and 3D rotating chiral designs. However, documentation of 3D zero Poisson's ratio (ZPR) honeycombs remains limited in academic literature, and two-dimensional ZPR honeycombs have yet to fully meet the criteria for complex adaptive morphing structures in morphing aircraft [38].

The IAR330 multirole helicopter is a model that remains in active use by the Romanian Air Force, with an anticipated operational lifespan extending approximately another ten years. The tail rotor blades of this helicopter are composed of a blend of aluminum alloys; however, a transition to composite materials could significantly enhance their performance. Recent research conducted in this field aims to evaluate the viability of a particular chlorinated polyethylene material as a replacement for the 5052 aluminum alloys currently utilized in the fabrication of the honeycomb core of the tail rotor blade. It also aims to elucidate the primary advantages and disadvantages associated with this transition. The necessity for weight reduction is more pronounced in helicopters than in airplanes, primarily because the engines must support the entire weight of the helicopter. Consequently, contemporary helicopters, such as the Eurocopter Tiger® and the NH90 produced by NH Industries, feature a composite material composition exceeding 80%, with significant proportions found in the aircraft fuselage, the main rotor hub and blades, as well as in the interior furnishing components. The blade's composite design incorporates a carbon fiber roving spar, a carbon fabric reinforced composite for the skin, and a lightweight 3D printed honeycomb core. The honeycomb structure, the focus of this study, consists of a series of hexagonal cells made from chlorinated polyethylene (CPE) infused with milled carbon fibers, produced via a fused deposition modeling (FDM) technique. The material's commercial designation is CPE CF112 Carbon. In conjunction with the upper and lower skins, these components constitute a sandwich-structured composite that exhibits remarkable resistance to external loads [39].

Additive manufacturing (AM), more commonly referred to as 3D printing, has brought about a substantial paradigm shift in the domain of polymeric material production, particularly within industries that prioritize rapid prototyping, customized products, and superior functional performance. Among the various AM technologies, fused filament fabrication (FFF), also referred to as FDM, has risen to prominence due to its ease of operation, cost-effectiveness, and compatibility with a range of thermoplastic polymers. Of particular interest are polylactic acid (PLA) and its carbon fiber-reinforced composite (PLA+CF), which have garnered significant attention due to their capacity to generate lightweight structures that exhibit enhanced mechanical strength. This renders them particularly well-suited for engineering applications that necessitate both structural robustness and minimized weight [40].

Additive manufacturing technology encompasses a diverse array of techniques, including stereolithography, inkjet printing, fused filament fabrication, selective laser sintering, and selective laser melting. This technology involves the deposition of materials layer by layer, primarily aimed at converting digital models into tangible objects. Among these, FFF stands out as the most prevalent additive manufacturing method due to its compatibility with a variety of materials, its quiet and safe operation, its ability to produce functional objects and components, the affordability of 3D printers, and its user-friendly nature. The intricate geometries and structures that are often challenging to achieve through conventional methods can be realized through FFF technology. Furthermore, FFF technology facilitates the creation, testing, and rapid modification of product prototypes when necessary. Research on the production of lightweight sandwich structures utilizing FFF technology can be categorized into several key areas: numerical testing and analysis of core structures; 3D printing and examination of gyroid cellular lattice structures; the fabrication of sandwich structures by adhering composite material sheets, specifically CFRP, to cores produced via additive technologies; and the 3D printing of sandwich structures intended for mechanical testing. The honeycomb structures created through additive technologies have been extensively studied in terms of their compressive strength, energy absorption capabilities, and the shape recovery effects exhibited by 3D-printed structures [41].

6. TESTS AND EXPERIMENTS

In the aerospace industry, stiffened panel structures (e.g., fuselage sections) are designed to be large-scale, complex mechanical tests based on smaller, simpler tests. These tests are used to define the complete structure of a new aircraft. The foundation of the pyramid is composed of a multitude of coupons, which are utilized to delineate the characteristics of the materials and their statistical variation. Through this method, the limits for tolerance to damage and environmental effects can be ascertained. Consequently, structural elements comprising predominantly small mechanical components are subjected to rigorous testing. The fuselage is essentially a large cylinder with strings and frames that stiffen the overall structure. In order to avert the occurrence of buckling collapse under overall bending and torsion, it is imperative to implement a comprehensive approach that encompasses a range of methodologies and considerations. Due to the intricacy and cost associated with the fuselage, partial structural studies are conducted on large, stiffened panels that are representative of the fuselage sections. The implementation of substantial tests enables the segregation of the skin stiffener, which is designated as "bonding" in this context.

This process facilitates the identification of "bonding" as a pivotal structural failure mechanism [6].

The inaugural composite wing box was certified as a component of a commercial civilian aircraft, and it has since been utilized extensively by NASA. In the case of the fuselage, the initial step involves identifying one or more of its rigid panels as critical. Instead of subjecting the entire structure to examination, one or more panels are subjected to representative design loads to meet the structural requirements of the entire fuselage [26].

As aircraft technology advanced, particularly during and after World War II, there was an increasing need for systematic static testing to ensure safety and reliability. The post-war period witnessed a transition towards more formal testing methodologies, influenced by standards established by the military and civil aviation sectors [3].

A series of mechanical tests were conducted to assess the structural integrity and performance of the blade. Static tests were conducted to evaluate the blade's torsional and bending stiffness, as well as the position of its elastic axis. Dynamic tests were performed to measure the blade's vibration characteristics, including its natural frequencies, vibration modes, and damping ratio. Additionally, blade fatigue tests were conducted to detect laminate separation, tolerance, and distortion of the structural cross-sections [2].

The evaluation of composite wings presents a series of distinctive challenges, including the intricacies of layering, the necessity for impact resistance, and the anisotropic characteristics of the materials. It is imperative to address these issues in a comprehensive manner during the testing phase. The building block approach delineated in the European Union Aviation Safety Agency (EASA) AMC 20-29 furnishes a structured framework for executing both static and fatigue tests on composite wings. During the design stage of the wing, the engineering team identified critical load scenarios through the analysis of shear force and bending moment along with potential failure modes. To validate the wing's design, the team was tasked with demonstrating its ability to endure the applied forces and moments, ensuring it meets the ultimate load requirements [3].

To gain a deeper understanding of the mechanical performance of the honeycomb core under compressive loading, the deformation behavior of its internal structure was closely examined. Observations indicated that, apart from the peripheral regions of the specimen, the internal hexagonal cells deformed uniformly, maintaining their integrity without noticeable slippage during compression. As the applied load increased, structural failure initiated in the walls of the hexagonal cells, resulting in localized collapse and the formation of superimposed honeycomb layers. These findings provide valuable insights into the load-bearing mechanisms and progressive failure modes of honeycomb cores, which are critical for optimizing their design and ensuring structural reliability in aerospace applications [19].

7. COMPARATIVE ANALYSIS OF HONEYCOMB COMPOSITE MATERIALS

Honeycomb sandwich composites are extensively utilized in aerospace structures due to their exceptional strength-to-weight ratios, stiffness, and energy absorption capabilities. The overall performance of these sandwich structures is critically influenced by three main components: the face sheet materials, the honeycomb core architecture, and the adhesive bonding interface that unites these elements. The aerospace sector employs a diverse range of materials for these components to optimize structural efficiency while minimizing weight, which is paramount for flight performance and fuel economy.

7.1. Components of honeycomb sandwich structures

Honeycomb sandwich panels typically consist of:

• *Face sheets.* These are the outer layers that carry in-plane and bending loads. Common materials include CFRP, glass fiber reinforced polymers (GFRP), aramid-epoxy composites, and thermoplastic composites. CFRP is favored for its high stiffness and strength-to-weight ratio, while GFRP and aramid composites offer cost and impact resistance benefits.

• *Core materials*. The core provides thickness to the sandwich panel, greatly increasing bending stiffness with minimal weight addition. Typical core materials include aluminum honeycomb, Nomex® (aramid paper) honeycomb, carbon honeycomb, and ceramic foams. Aluminum honeycomb is widely used due to its good mechanical properties and manufacturability; however, it is susceptible to galvanic corrosion when in contact with carbon fiber face sheets, necessitating careful material pairing or protective coatings. Nomex® honeycomb, made from phenolic resin-coated aramid paper, offers excellent FST performance and is preferred in applications requiring enhanced thermal resistance and lightweight properties.

• *Adhesive/bond layers*. The integrity of the sandwich structure heavily depends on the bond between the face sheets and the core. Epoxy-based adhesives and film adhesives are commonly used due to their high strength, environmental durability, and compatibility with composite materials. Advanced aerospace adhesives also provide resistance to thermal cycling, vibration, and moisture ingress, which are critical for long-term structural reliability.

7.2. Mechanical and functional performance

Honeycomb sandwich composites exhibit high compressive strength along the cell walls and significant shear strength perpendicular to the cell walls, enabling them to withstand complex loading scenarios encountered in aerospace environments. The hexagonal geometry of the honeycomb core mimics natural structures like beehives, providing optimal strength-to-weight efficiency. The core typically consists of up to 95% enclosed air, which contributes to the low density of the panels.

However, the structural performance can be compromised by environmental factors such as pressure differentials, temperature variations, and humidity changes experienced during flight. For instance, unvented honeycomb cores can develop internal pressurization stresses due to trapped air or cryopumping effects, potentially leading to face sheet/core debonding. Such failures have been documented in aerospace history, including incidents in space systems and commercial aircraft, emphasizing the need for vented core designs or rigorous testing protocols to ensure bondline integrity under operational conditions.

7.3. Material trade-offs and selection criteria

Each honeycomb composite system presents specific trade-offs:

• Aluminum honeycomb cores provide excellent mechanical properties and are cost-effective but require careful isolation from carbon fiber face sheets to prevent corrosion. They are less suitable for high-temperature environments unless specialty metals like titanium or steel are used.

• Nomex® honeycomb cores offer superior FST performance and are lightweight, making them ideal for interior aircraft components such as flooring, sidewalls, and ceilings. Their phenolic resin coating enhances thermal resistance, though they may have lower compressive strength compared to metallic cores.

• Ceramic and carbon honeycomb cores are employed in high-temperature or specialized applications due to their thermal stability, but they are generally more expensive and challenging to manufacture.

• Face sheet materials must be selected based on desired stiffness, strength, impact resistance, and compatibility with the core. For example, carbon fiber face sheets deliver high stiffness but are prone to galvanic corrosion when paired with aluminum cores. Glass or aramid fiber face sheets can mitigate this issue but may compromise stiffness.

• Adhesives must provide strong bonding, environmental resistance, and compatibility with both face sheets and core materials. Epoxy adhesives are standard, with specialized potting and edge-fill compounds used to enhance mechanical strength and protect against moisture and vibration.

7.4. Advances and challenges

Recent advances in composite manufacturing, such as automated fiber placement and out-of-autoclave curing, have enabled more complex and reliable honeycomb sandwich structures. Emerging multifunctional composites incorporating nanomaterials and smart sensing capabilities promise enhanced performance and health monitoring.

Nonetheless, challenges remain in ensuring long-term durability against environmental stresses, preventing debonding under pressure differentials, and balancing cost with performance. The aerospace industry continues to refine material combinations and bonding techniques to optimize these structures for both primary and secondary aircraft components.

8. EVALUATION OF HONEYCOMB COMPOSITES FOR AVIATION

Honeycomb sandwich composites derive their multifunctional performance from the synergistic interaction between high-strength face sheets and lightweight core materials. The structural behavior, energy absorption characteristics, and environmental durability of these systems depend not only on the choice of constituent materials but also on the microstructure of the core (cell geometry, density, and thickness) and the type of adhesive interface. Below, the principal material systems used in aerospace applications are analyzed based on experimental and numerical research findings.

1. Nomex®/CFRP systems: balancing weight and processability.

Nomex® aramid paper honeycomb cores combined with CFRP face sheets are widely adopted in commercial aircraft components such as control surfaces, radomes, and interior panels. Their main advantages include:

• high specific stiffness (~40–50 kN·m/kg) and good compressive strength (2–3 MPa);

• excellent formability for curved surfaces and complex contours;

• dielectric transparency, suitable for radar dome applications.

However, they are thermally limited (~180 °C) and hygroscopic, meaning they are prone to moisture ingress, which leads to interfacial debonding, core swelling, and long-term degradation. Advanced sealing techniques and use of hydrophobic coatings have been proposed, yet they add manufacturing complexity.

2. Aluminum honeycomb/GFRP or CFRP systems: high stiffness, corrosion trade-off.

Aluminum honeycombs (typically 5052-H39 or 3003 grades) exhibit superior compressive modulus (~120 MPa) and excellent out-of-plane shear performance. Their applications extend to aircraft floors, flaps, nacelles, and fairings. When bonded to glass fiber or carbon fiber face sheets, the system offers:

• high fatigue resistance and structural rigidity;

Table 1. Comparative properties of honeycomb core–face sheet systems in aerospace applications.

Core material	Face sheet	Key mechanical properties	Advantages	Limitations	Typical applications	References
Nomex® (aramid paper)	CFRP (carbon/epoxy)	Compressive strength: 1.5–2.5 MPa Shear modulus: ~80 MPa	Lightweight, flame-resistant, easy forming, dielectric	Moisture absorption, low thermal stability (<180 °C)	Cabin panels, radomes, flaps, UAV fairings	[16,17]
Aluminum (5052, 3003)	GFRP/CFRP	Compressive strength: 5–8 MPa Shear modulus: ~150 MPa	High stiffness, fatigue resistance, cost-effective	Heavier than polymers, galvanic corrosion with CFRP	Engine nacelles, landing gear doors, helicopter blades	[2,15]
SiC foam	SiC/SiC CMC	Strength: > 120 MPa Thermal stability: > 1300 °C	Ultra-high temperature resistance, oxidation stability	Brittle, expensive, difficult fabrication	Turbine components, hypersonic vehicles	[8,9]
Gradient-density polymer (PU, TPU)	CFRTP (carbon/PEEK)	Energy absorption: > 60 J/g Shear modulus: variable	Tunable stiffness, morphing capability, additive manufacturing compatibility	Low shear strength, process sensitivity	UAV wings, crash protection panels, adaptive skins	[21,29]
Metallic foam (Al, Ni)	Al alloy / CFRP	Energy absorption: 100–150 kJ/m^3 Compressive modulus: ~100 MPa	Excellent crashworthiness, acoustic damping	Difficult to bond uniformly, density variation	Rotorcraft armor, missile fairings, crash zones	[19]
Carbon-loaded honeycomb (RAM)	GFRP/hybrid laminates	EM absorption: up to 40 dB Shear strength: ~70 MPa	Radar stealth + structural support, low RCS	Band-limited performance, increased weight	Nose cones, stealth UAVs, inlet linings	[18]

• thermal stability up to ~200–250 °C, depending on adhesive system.

The major drawback is the risk of galvanic corrosion, especially when aluminum cores are in direct contact with CFRP under humid or marine conditions. To mitigate this, dielectric isolation layers, corrosion-inhibiting primers, or hybridization with GFRP are employed.

3. SiC/SiC ceramic matrix composites: extreme temperature applications.

CMCs, particularly SiC/SiC systems, have been designed for applications where resistance to high thermal loads (> 1300 °C) and oxidative environments is critical. Their application domains include:

• turbine outer rings and engine liners;

• supersonic inlet ducts.

They exhibit high creep resistance and thermal shock stability, but remain intrinsically brittle (fracture toughness ~2–3 MPa·m$^{1/2}$) and difficult to process, requiring CVI or prepreg–MI methods. Their cost and complexity currently restrict widespread application to defense and space-grade components.

4. Functionally graded honeycomb cores: energy absorption optimization.

Gradient-density cores—achieved by varying cell height, wall thickness, or material composition across the structure—can localize deformation and optimize impact absorption. Recent studies on hourglass-shaped honeycomb configurations and bioinspired cellular geometries have demonstrated:

• enhanced specific energy absorption (>60 J/g);

• mitigation of stress concentration and crack propagation;

• customization for UAV crashworthiness and deployable structures.

Manufacturing such structures via additive manufacturing techniques (e.g., FDM, SLS) has enabled topology optimization and integration of multi-material interfaces, albeit with challenges in resin removal and powder retention.

5. Radar-absorbing honeycomb structures: dual mechanical-EM functionality.

In military and stealth applications, HASs provide simultaneous load-bearing capability and reduction of radar cross-section (RCS). They are typically fabricated by infusing radar absorbing materials (RAMs) into honeycomb cells or coating the internal walls with carbonyl iron or ferrite-loaded epoxies.

Such structures are optimized to function in specific EM frequency bands (e.g., X-band: 8–12 GHz), and research shows up to 40 dB absorption across wide bandwidths. Mechanical stiffness can be reduced due to RAM inclusion, requiring reinforcement of the face sheets or integration with stiffened skins.

6. Metallic foams and hybrid core panels: crashworthiness and damping.

Metal foams (e.g., Al, Ni, Ti) and foam-filled honeycomb cores provide significant benefits in energy dissipation, blast mitigation, and acoustic damping. These structures are particularly valuable in:

- missile fairings;
- rotorcraft crash attenuators;
- protective underbody panels.

They exhibit high volumetric energy absorption (~100–150 kJ/m^3) but impose weight penalties, making them more suitable for localized reinforcement rather than full-airframe structures. Foams may also suffer from density variation and pore coalescence, leading to inconsistency in mechanical performance.

8.1. Honeycomb structure for morphing wing

A recently developed 3D ZPR honeycomb structure has been created to satisfy the flexible deformation needs of morphing aircraft. This 3D ZPR honeycomb demonstrates the capacity to undergo deformation in all three principal directions while preserving smooth edges and isotropic properties. Morphing aircraft possess the capacity to augment their aerodynamic flight envelopes through the manipulation of their shapes, thereby achieving a notable enhancement in flight efficiency and range, in addition to the capacity to execute a variety of tasks. The honeycomb structure, with its lightweight composition and remarkable out-of-plane stiffness, renders it an optimal material for morphing aircraft. In order to address the limitations of the positive Poisson's ratio / negative Poisson's ratio (PPR/NPR) honeycomb and fulfill the deformation requirements of morphing structures, researchers have developed a range of ZPR honeycombs. These include accordion honeycombs, positive / negative zero Poisson's (PZP-NZP) hybrid honeycombs, SILICOMB® honeycombs, fish cell honeycombs, chiral cellular structures, four-pointed star shape honeycombs, and reconfigurable mechanism module structures. These ZPR honeycombs have been the subject of extensive research and investigation for their initial application in morphing skin. It is noteworthy that the honeycomb exhibits a four-pointed star shape, capable of deforming in two orthogonal in-plane directions while preventing out-of-plane warping deformation. Subsequent proposals have involved the optimization of honeycombs to further enhance the deformation capabilities of the four-pointed star honeycomb structure [38].

It has been demonstrated that thin structural components, including extensive covering plates utilized in aerospace protection systems and the vertical stabilizers of aircraft, are significantly impacted by gravitational forces (and/or acceleration). Consequently, it is imperative to investigate the influence of the gravitational field on the mechanical properties of these structures. Such slender structural elements typically encompass large-scale covering shells or plates utilized in aerospace protection structures, vertical stabilizers of accelerated aircraft or missiles, and specific system components that are significantly affected by fluctuating gravity. These relatively thin structures experience hypergravity as the flight vehicle accelerates. Therefore, it is imperative to investigate how the mechanical behaviors of thin-walled structures, such as buckling and vibration, are influenced by the gravitational field. The mechanical performance of a monolithic plate within a gravitational field constitutes a fundamental component of thin structures, and as such, has been the subject of extensive research. In the initial phase, the stability and vibration characteristics of a rectangular plate subjected to its own weight or acceleration-induced body force were analyzed by considering the body force as linearly varying in-plane distributed loads (IPDLs). In lieu of solid plates, sandwich structures are extensively employed in aircraft, aerospace vehicles, satellites, missiles, and analogous applications. Specifically, ultralight sandwich plates featuring thin face sheets and periodic lattice truss cores, such as triangular corrugated (TCOR) plates and hexagonal honeycombs (HHON), are garnering increasing interest due to their enhanced load-bearing capabilities and additional multifunctional properties, including energy absorption, active cooling, and noise reduction. For instance, research has demonstrated that TCOR and HHON sandwich plates exhibit remarkable bending strength, resistance to blasts, and the capacity to absorb impact energy. Nevertheless, while the effects of hyper gravity or acceleration on the vibration or stability of sandwich plates warrant significant investigation, similar to monolithic plates, only the current authors have successfully explored how a corrugated sandwich plate would experience buckling when subjected to distributed body forces under various boundary conditions. At present, the vibration characteristics of ultralight cellular-cored sandwich plates exposed to impul-

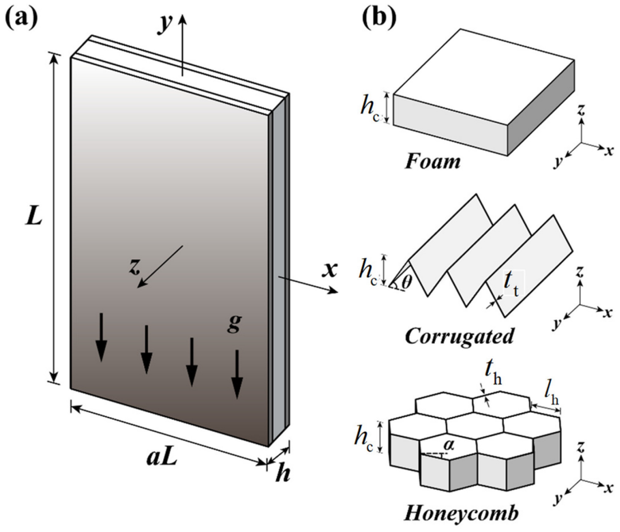

Fig 5. Common sandwich core structures used in lightweight panel design. The figure illustrates four typical cellular core types: (a) cellular sandwich plate subject to linearly varying in-plane distributed load and (b) cellular foam, triangular corrugated metal plate, and hexagonal metal honeycomb as sandwich core. (Top right) Foam: a solid block of foam material characterized by thickness h_c, providing uniform support. (Middle right) Triangular corrugated: metal plates shaped in a triangular wave pattern with parameters including thickness t_t, height h_c, and angle θ, enhancing stiffness and load distribution. (Bottom right) Hexagonal honeycomb: a structure composed of hexagonal metal cells defined by cell height h_c, wall thickness t_h, cell length l_h, and the hexagonal angle α, offering a high strength-to-weight ratio. Reproduced from Ref. [42], under the terms of CC BY-NC 3.0 license. © 2023 F.H. Li et al.

sive dynamic loading remain to be fully elucidated. In the realms of nature and engineering, the utilization of HHON sandwiches is more prevalent (Figure 5). The search yielded the presence of TCOR sandwiches. Consequently, this section aims to explore the potential for enhancing in-plane mechanical properties. In the field of performance, a transition from metallic face sheets to composite face sheets has been observed in the construction process. The plates in question are of the type known as “HON” [42].

9. MULTIFUNCTIONAL DESIGN OF COMPOSITE HONEYCOMB MATERIALS

9.1. Thermal property design

Fiber-reinforced composite sandwich structures with light-weight and excellent mechanical properties are remarkable for building spacecraft. Meanwhile, the thermal property of composite honeycomb materials also received lots of attention. The thermal conductivity of sandwich panels with different kinds of fiber-reinforced composites was studied by analytical prediction and experimental measurement [43]. In the analytical model, the thermal resistance of a sandwich panel is the sum of the thermal resistances of skins and core. Steady state thermal transmission and uniaxial heat flux were considered in analytical prediction. Honeycomb cores fabricated by the vacuum-assisted resin transfer molding method using polyester resin and jute, glass and carbon fiber fabrics were respectively bonded with glass and jute fiber composite skins. The thermal conductivities of those skins and cores were separately measured as reducing the total amount of experiments to be performed. The thermal conductivity of sandwich panels was measured and calculated with the composite theory from the thermal conductivity values of skins and cores, and having a good agreement with analytical prediction. It was found that all the sandwich panels excepted to the ones made with carbon fiber honeycomb can be considered as appropriate thermal insulators.

Fiber-reinforced composite honeycomb materials possessing both good mechanical properties and high thermal conductivity are important for the aerospace industry. A type of composite honeycomb sandwich structure made by the interlocking method was designed to improve the out-of-plane thermal conductivity [44]. The theoretical model was constructed and investigated. It shows the most efficient method for increasing the out-of-plane thermal conductivity of sandwich structure is decreasing the interface thermal resistance of the honeycomb core. Highly oriented graphite film which in-plane thermal conductivity is up to 1500 W/m·K was used to coat the composite laminates before the interlocking process. The interface thermal resistance of the honeycomb core is decreased by coating this film. Besides, this value is able to decrease by increasing the volume content of highly oriented graphite film. After fabrication, specimens were tested to measure the out-of-plane thermal conductivity of composite honeycomb sandwich structure. Finally, the maximum experimental result attains to 13.53 W/m·K, which is almost 26 times more than the traditional composite honeycomb sandwich structures. This kind of honeycomb material is suitable for high-end heat dissipation applications.

9.2. Microwave absorption property design

Radar absorbance is an important factor for stealthy structures. However, the microwave absorption abilities of carbon fiber reinforced composites and glass fiber reinforced composites are unsatisfactory. A stretching dominated honey-comb grid filled with spongy materials was designed to combine mechanical properties of fiber-reinforced honey-comb with microwave absorption ability of foam [45]. The reflectivity of the structure was measured in the darkroom at normal and oblique incidences. It was found the grid panels made by carbon fiber reinforced composites and glass fiber reinforced composites possess good absorption capacity at the range of 4–18 GHz frequencies. Glass fiber-reinforced grid shows better absorp-

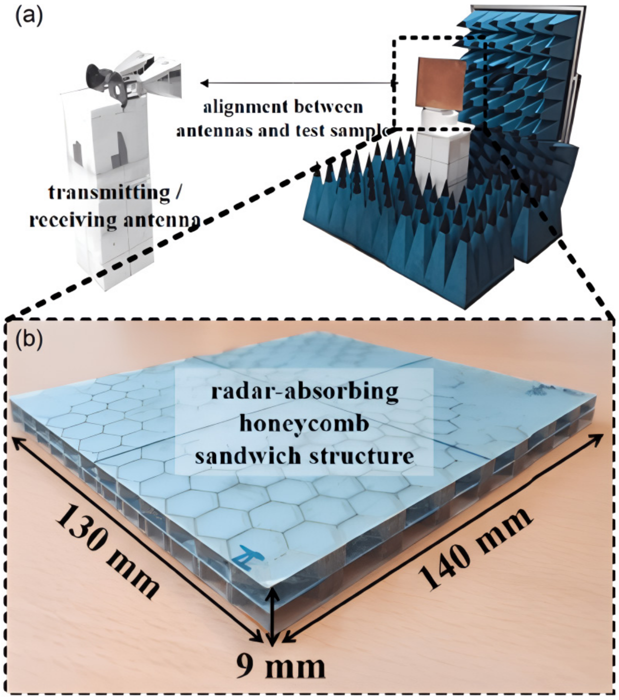

Fig. 6. Experimental platform and radar-absorbing composite honeycomb design. (a) The test platform for the measurement of the return loss and echo radar cross-section level of radar-absorbing honey-comb material; (b) honeycomb sandwich panel with nickel-coated glass fabric. Reproduced from Ref. [46], under the terms of CC BY-NC 4.0 license. © 2020 B. Kwak et al.

tion ability than carbon fiber-reinforced grids. The better reflectivity and wider bandwidth are shown in the thicker panel. The periodic grids improve the absorption abilities at high frequencies but decrease these abilities at low frequencies. According to the experimental data, the reflectivity of this foam-filled grid panels is even better than the pure absorbing foam panels.

A radar-absorbing honeycomb material with nickel-coated glass fabric was proposed to reduce the echo radar cross-section level of the leading edge of a NACA 0012 wing airfoil [46]. This leading edge of the wing was composed of two honeycomb core and three face sheets to implement broad radar absorption. The electrical properties of the glass fibers were modified by an electroless nickel plating technique. Dispersing conductive nanoparticles or metal magnetic micro-powders in composite materials, which result in inferior absorbing performance and design uncertainty were avoided. The broadband radar absorption ability of these proposed structures was studied by measuring the return loss and echo radar cross-section level, as shown in Figure 6. It exhibited –10 dB microwave absorption in the frequency range of 5.8–16.3 GHz and a resonance peak of –38.1 dB at 8.2 GHz under transverse magnetic mode. The measurements indicated that RCS of the leading edge decreased by approximately 10 dB for vertical polarization and by 8 dB for horizontal polarization within the frequency range of 6.0–17.8 GHz. Complementary simulations using a computer model confirmed that the echo RCS levels of the NACA 0012 wing's leading edge were reduced by up to 10 dB for both horizontal and vertical polarizations, spanning frequencies from the C-band to the Ku-band. These results demonstrate the effectiveness of the nickel-coated glass fiber honeycomb in providing broadband radar absorption, highlighting its potential application in stealth aircraft structures.

9.3. Sound absorption property design

Sound absorption property of honeycomb materials made by flax fibers with polyethylene matrix was studied in Ref. [47]. The sound absorption coefficients of honeycomb sandwich panels with continuous fibers or short fibers were measured. It was found the mean values of specimens are between 0.1 and 0.4 at frequencies from 100 Hz to 4 kHz with intervals of 1/3 octaves. The acoustic property of the sandwich structure is more linked to the materials rather than the structure. The primary factor of the sound absorption coefficient changes with frequencies. The type of reinforced fibers exerts more influence at the lower frequencies. The sound absorption coefficient of continuous fiber-reinforced composites is higher than the short ones. Meanwhile, the fibrous arrangement and the damped viscoelastic matrix behind the face sheets play dominant roles at mid-high and higher frequencies, respectively. It is interesting that the modal damping value of sandwich panel with fiber-reinforced honeycomb core is lower than the panel with an unreinforced honeycomb core, which suggests that the viscoelastic properties of the matrix material control the modal damping value. However, the honeycomb core only made by matrix material show poor mechanical properties. Fiber-reinforced honeycomb materials show a reduction of about 40% in model damping and an improvement of higher than 100% in mechanical properties. So, how to define the best available solution for balance vibration level with mechanical property is important.

A sound-absorbing periodically arrayed structure was designed to suppress the radiant noise of a submarine [48]. Carbon fiber honeycomb as the skeleton of the absorber was used for bearing hydraulic pressure. The gradient resonant cavity layer, the sound-permeable layer and the viscoelastic bottom layer of the absorber employed different types of polyurethane composites. The sound absorption coefficient of the absorber was predicted by the approximate multi-layered sound-absorption theory, which is based on a modified transfer matrix method. After that, the coefficient is measured by experiments. It was found the coefficient achieves 0.9 in the frequency range of 2400–10000 Hz under the hydraulic pressure of 1.5 MPa. The improvement in sound absorption at specific frequency points was also analyzed by simulating the displacement, radial velocity and acoustic pressure distribution of absorber. The experimental results agree with the theoretical model and simulation. It shows the addition of carbon fiber honeycomb absorber changes the sound field distribution in a positive sense. Hence, carbon fiber honeycomb absorber has the potential for application in submarine noise insulation and anti-sonar detection.

9.4. Mechanical metamaterials design

Mechanical metamaterials exhibit unconventional behaviors by rational design of artificial micro-structures. With a negative Poisson's ratio, auxetic honeycomb is a typical example of metamaterials. However, the plastic failure of pure materials limits the improvement of this special property. Auxetic honeycomb structures reinforced by continuous fiber were designed and fabricated by 3D printing technology [49]. A systematic study including analytical models, printing path-based finite element model and in-plane experiments was carried out to investigate the effective stiffness and Poisson's ratio of continuous fiber-reinforced thermoplastic composite auxetic honeycomb structures. Another group of auxetic honeycomb made by pure polylactic acid material was fabricated and tested as a comparison. Compared with pure matrix, continuous fiber-reinforced composites inhibit crack growth in the honeycombs. The composite stiffness and energy absorption of the auxetic honeycombs are increased by 86.3% and 100% by reinforcing continuous fibers. Besides, Poisson's ratios are smaller than pure material honey-combs. The in-plane mechanical properties of honeycomb can be controlled by unit cell geometric parameters and fiber volume fraction. Fiber-reinforced composite provides a new approach for developing mechanical metamaterials.

The 3D ZPR honeycomb structure consists of an orthogonal configuration of four-pointed star structure lattices. Due to the specimen's inherent symmetry, the rotation at the juncture of the cell arms is found to be null. The 3D ZPR honeycomb demonstrates independent deformations in the x, y, and z axes when the rotational deformation at the junction is disregarded [38].

10. IMPROVEMENT DESIGN FOR MECHANICAL PROPERTY

10.1. Hybrid designs of honeycomb topology

The hybrid design is a method to improve the mechanical properties of honeycomb material by combining honeycomb with other topology structures. The simplest hybrid method is combing honeycomb with foams. A hybrid carbon fiber-reinforced honeycomb with filling polymethacrylimide (PMI) foam was proposed to enhance the anti-pressure ability [50]. The honeycomb was fabricated by the interlocking method. Square prismatic foams were inserted into the honeycomb hole and bonded together. This hybrid structure was studied by the theoretical model, numerical simulation and experiments. It was found the foam-filled honeycomb possesses higher compressive strength than empty honeycomb materials. However, the effects of the filled foams on the compressive strength gradually reduced with the increase of relative density. The peak stresses of these two materials have little difference when the relative density is higher than 0.15.

A hybrid design combing honeycomb with a hollow lattice truss was proposed to improve the buckling resistance [51]. Hot press molding method fabricated the strips combing ribs and hollow lattice truss. The hybrid honeycomb-lattice was prepared after interlocking the strips together. The out-of-plane compressive property of the hybrid honeycomb was tested and compared with the square honeycomb. Composite hybrid honeycomb fails to exhibit better out-of-plane compressive behavior than square honeycomb as immature technology derives many defects at the slots. However, compared with polymeric square honeycomb, the polymeric hybrid honeycomb with perfect geometries shows better compressive characteristics in stiffness and strength. It demonstrates that hybrid designs can provide a new method for new materials and structures providing better mechanical properties.

10.2. Hierarchical designs of honeycomb topology

Hierarchical design is of efficiency to improve the mechanical properties of light-weight material. In general, hierarchical designs of honeycomb topology transform solid honeycomb walls to sandwich structures for resisting structural buckling at low densities. The interlocking method is widely used for manufacturing hierarchical honeycomb structures due to the step-by-step fabrication process. The hierarchical honeycomb-lattice structures were designed and studied in Refs. [52,53]. The square, triangular and Kagome honey-comb were fabricated by interlocking glass-fiber weaved textile sandwich panels. The analytical models and the experiments revealed the out-of-plane compressive properties and plastic deformation mechanisms of the hierarchical honeycomb-lattice structures. It was shown that hierarchical design restricts rib buckling and improves the plastic moment. The compressive stress-strain curves have stable displacement plateaus and high compressive strength. Larger densification strains have also occurred in the hierarchical honeycomb with smaller relative densities. Hence, hierarchical honeycomb-lattice structures possess excellent energy absorption capacity and load-weight efficiency. The hierarchical honeycomb-foam structures were proposed to enhance specific out-of-plane compressive property at low densities. The sandwich panels with PMI foam core

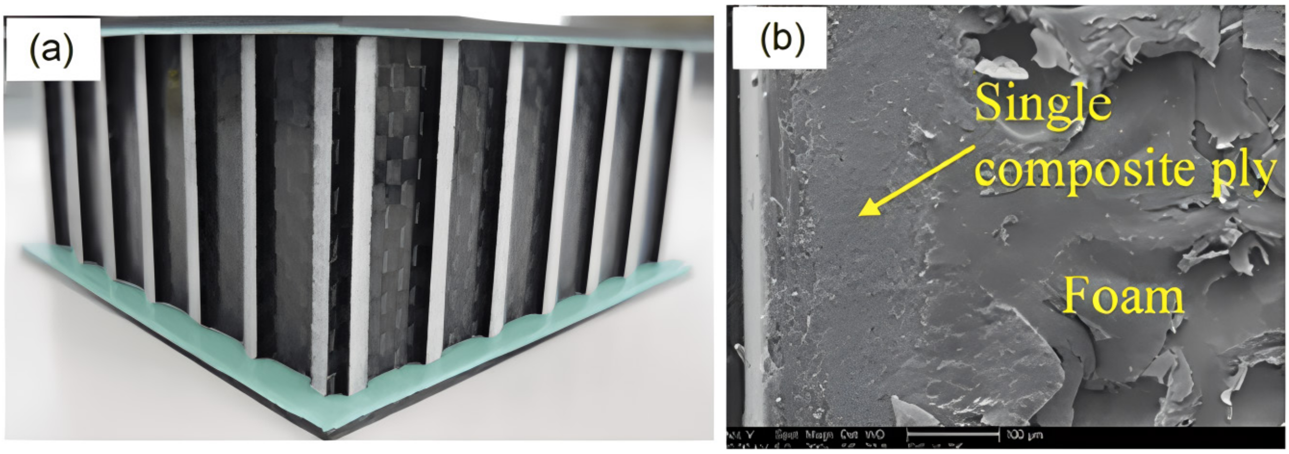

Fig. 7. Hierarchical sandwich panel with honeycomb-foam core. (a) Photograph of the full sandwich panel illustrating the hierarchical honeycomb-foam core structure. (b) Cross-sectional images showing the interface between the composite ply and foam, highlighting the adhesion and microstructural integration. Reproduced from Ref. [55], under the terms of CC BY-NC 4.0 license. © 2018 L. Feng et al.

and glass fiber reinforced composite faces were made by hot press molding method. Then, the hierarchical honeycomb was assembled by interlocking sandwich panels with PMI foam core and glass fiber reinforced composite faces [54]. The hierarchical honeycomb sandwich structures were studied by analytical prediction, simulation and experiments. It was shown the out-of-plane compression property of hierarchical honeycomb sandwich panel is higher than an equivalent sandwich panel with a monolithic honeycomb core. The sandwich panels with a hierarchical honeycomb-foam core made by carbon fiber reinforced composites were also fabricated by the interlocking method [55]. Photograph of a sandwich panel with hierarchical honeycomb-foam core and cross-section images of the interface of composite ply and foam are shown in Figure 7. The out-of-plane compression property and in-plane shear property of hierarchical honeycomb with different relative densities were studied by analytical models and experiments. Compared to the sandwich structures with a monolithic honeycomb core, the specific out-of-plane compressive strength and the specific shear strength of hierarchical honeycomb-foam sandwich structures improves to 330% and 180%, respectively. It provides new opportunities for light-weight sandwich structures.

A hierarchical honeycomb-honeycomb cylindrical structure was designed to enhance energy absorption ability [56]. Sandwich panels with glass fiber reinforced composite faces and polypropylene honeycomb core was used as honeycomb ribs. Two types of hierarchical honeycomb-honeycomb cylindrical structures were fabricated and tested under axial compressive loadings. It was found the crushing efficiency of the optimized cylindrical structures can be improved from 0.4 to 0.7. The optimized cylindrical structures exhibited great deformation recovery ability, even over 80% of initial height. Besides, good reloading and energy absorption properties are higher than 13% and 12% of initial ones respectively. It has an advantage over the conventional energy absorbers.

The hexagonal honeycomb structure, which has its origins in nature, has found extensive applications in engineering. A comprehensive examination of its elastic and nonlinear mechanical properties has been conducted through theoretical analysis, numerical analysis, and experimental validation. Conventional positive Poisson's ratios (PPR) hexagonal honeycomb has been built upon by researchers who have introduced a range of innovative honeycomb metamaterials that display negative Poisson's ratios (NPR) and zero Poisson's ratios (ZPR). The topological configurations of NPR honeycombs encompass re-entrant hexagonal honeycombs, chiral honeycombs, star honeycombs, and double-arrow honeycombs [38].

A successful design incorporates a lattice structure that is tailored to the specific stress conditions the structural component will encounter. This objective can be achieved through the optimization of the lattice topology, a technique that generates a complex, solid lattice hybrid structure by selecting the appropriate lattice configuration to occupy the material removal area of the topologically optimized structure within a defined relative density range. A judicious choice of the lattice type, in conjunction with the precise adjustment of the relative density range for the lattice filling, has the potential to enhance the mechanical properties of the solid lattice hybrid structure. At present, the lattice types that have the widest application include foam porous structures, metal lattice structures, and triply periodic minimal surface (TPMS) porous structures. Among these, the metal lattice structure demonstrates excellent unidirectional load-bearing capabilities, whereas the TPMS porous structure offers self-supporting characteristics that significantly enhance its design flexibility. It is noteworthy that both types of lattices are deemed suitable for the optimization design of heat-resistant, unidirectional load-bearing structures [57].

The spider web is regarded as one of nature's most exquisite creations and is categorized as a distinct form of pre-stressed system (tensional integrity). This category demonstrates exceptional specific strength and elongation properties that surpass many synthetic materials, including Kevlar and various grades of steel. The design of the web, drawing inspiration from biological principles, features a reiterated hierarchical structure composed of sub-hexagons interconnected by linking webs at various scales. When this hierarchical structure is positioned along the periphery of the cell walls within the structure, it exhibits enhanced stability and a greater number of progressive folds in comparison to conventional and self-similar hexagonal honeycombs when subjected to in-plane compression. Furthermore, the initial order of the hierarchical structure exhibited a significant elastic response and a considerable capacity for energy absorption, characteristics attributable to its unique mixed mode of bending and stretching deformation behavior [58].

The analysis focuses on four categories of sandwich plates: the homogeneous (monolithic) plate, the aluminum foam-cored sandwich plate, the TCOR-cored sandwich plate, and the HHON-cored sandwich plate. For the sake of simplicity, it is assumed that the face sheets of all these plates are constructed from aluminum alloy. The aluminum foam utilized in this study possesses closed cells and exhibits the following material characteristics: density of 540 kg/m^3, viscosity of 0.3, and elasticity of 405 MPa. It is evident that the frequency of the foam-cored sandwich plate is nearly three times greater than that of the homogeneous plate. In the case of the TCOR and HHON sandwich plates, the disparity is even more pronounced, with their frequencies exceeding four times that of the homogeneous plate. Furthermore, the sandwich plates exhibit substantially larger critical buckling IPDLs compared to the homogeneous plate, thereby affirming that the former demonstrates a significantly higher level of stability. It has been demonstrated that, among the three types of cellular cores, the TCOR and HHON cores are more effective in improving the structural stability of sandwich constructions than the foam core. In addition, the TCOR sandwich plate exhibits the highest frequency and the largest critical buckling IPDL, thereby demonstrating superior performance in comparison to the other variants. A comparison of the structural properties of sandwich plates with various core types reveals that the TCOR and HHON sandwich cores possess greater thickness than the foam core when subjected to the same mass constraint. This phenomenon can be attributed to the markedly lower equivalent core density exhibited by both TCOR and HHON in comparison to that of foam. Consequently, the enhancement of core thickness contributes positively to the stability of the sandwich plate, as it enhances the overall flexural stiffness of the sandwich structure. The flexural stiffness of a structure is directly proportional to its cubic thickness. However, it is imperative that the core plates of TCOR and HHON do not exhibit local buckling when loads are applied; consequently, the core must not be excessively thin. Furthermore, if the core thickness remains constant while only the core density is increased, the critical buckling IPDLs of the structure will rise, although the fundamental frequency will initially increase before subsequently decreasing. As the core density increases, the overall stiffness of the structure concomitantly rises, resulting in an increase in its mass. A comparable structural parametric analysis has been previously documented in our extant research [42].

The hexagonal configuration of separate cells within the honeycomb structure provides an ideal balance of strength and weight efficiency, making it an exceptionally effective design for load-bearing applications. The geometry of the honeycomb core is widely used in aerospace engineering, the military, and other industries that require lightweight, robust materials. Although the honeycomb core is a highly effective and widely adopted design, alternative biomimetic designs may offer superior efficiency and performance in sandwich-structured composites [59].

Auxetic honeycomb structures, distinguished by NPRs, are regarded as pioneering engineering metamaterials. These structures are notable for their exceptional relative stiffness and strength, as well as their augmented energy absorption capabilities in comparison to conventional honeycombs. The present study investigates the implementation of these structures in composite-coated and honeycomb-core sandwich configurations. The existing literature encompasses a variety of auxetic topologies, including re-entrant cells, star-shaped porous cells with microstructural connectivity, chiral structures, and star arrowhead-shaped cells. Moreover, the existing literature expounds upon novel cell geometries that manifest NPRs, which are derived from the re-entrant cell and its subsequent modifications [60].

10.3. Biomimetic design of sandwich structure core

10.3.1. Diatom design

Diatoms are unicellular algae that represent a group of marine microorganisms (Figure 8). They joined the plant kingdom relatively late in the evolutionary process through a distinctive pathway. Researchers hypothesize that diatoms function as secondary endosymbionts, meaning their ancestors engulfed another eukaryotic organism. This led to the development of a four-layered membrane surrounding the chloroplasts acquired through this symbiotic relationship. Today, diatoms inhabit oceans, freshwater bodies, and even terrestrial soil around the world. Many scientists credit their success to their silicified cell walls, called frustules, which consist of two shells with remarkable shapes and complex patterns. These frustules protect the cell from mechanical damage. The silicates found in their skeletal structure are derived from nutrient absorption, and the frustules act as a protective outer layer against predators, providing exceptional stability. The highest degree of protection with minimal material usage results in optimal performance characteristics [59].

10.3.2. Double-helix design

The double helix structure is an extraordinary geometric configuration prevalent in nature (Figure 9). It can be observed at both the macroscopic and microscopic levels. Macroscopic helical formations can be seen in various organisms, such as shells, horns, plant tendrils, and sea pods. The double helix is a stable, hierarchical structure defined by the continuous rotation of two helical segments around a longitudinal axis. The exoskeletons of many arthropods, such as American lobsters and Japanese beetles, have remarkable structural characteristics that allow them to support their body weight and withstand external pressures. These exoskeletons often have similar structural morphologies. They are composed of a multilayered architecture, and the orientation and patterns of the exoskeleton's organization are fundamentally comparable. Helical geometry is also apparent at the microscopic scale, highlighting its potential for creating exceptionally stiff and strong structures. Consequently, this structure is now being used to reinforce various materials. For instance, it has been used to significantly enhance the mechanical properties of carbon nanotubes. The twist in the helix considerably enhances stability against bending or buckling, making this geometry ideal for use in sandwich cores [59].

10.3.3. Double-sine corrugated design

The double-sine corrugated structure is biologically inspired by stomatopods, marine organisms known for their powerful raptorial appendages used in burrow defense (Figure 10). They are known for their aggressive behavior and ability to defend their burrows with a powerful raptorial appendage. A specific subspecies of stomatopod, the peacock mantis shrimp features a heavily fortified telson that can be unfolded and extended forward, much like the striking appendage of a praying mantis. The dactyl club's mechanical response can be attributed to its structural makeup. It is a multi-phase composite comprising oriented crystalline hydroxyapatite, amorphous calcium phosphate, carbonate, and a highly expanded helicoidal arrangement of the fibrillar organic matrix. These characteristics provide effective mechanisms that safeguard against catastrophic failure during high-energy impacts.

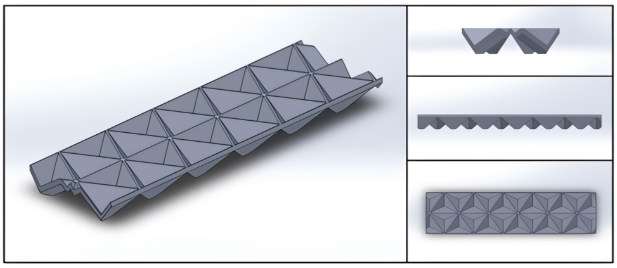

Fig. 8. Diatom Design of bioinspired honeycomb structures with two symmetric planes : 3D view (left); unit cells (top right); side view (middle right); and top view (bottom right). Reproduced from Ref. [59], under the terms of CC BY-SA 3.0 license. © 2023 C. Kunzmann C. et al.

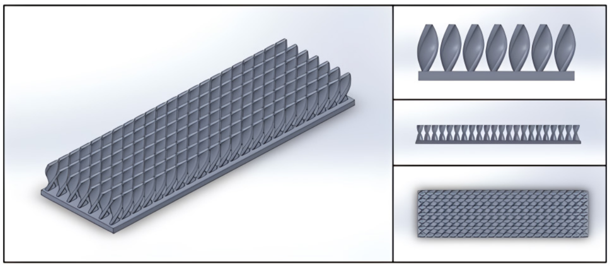

Fig 9. Double-helix design: 3D view (left); unit cells (top right); side view (middle right); and top view (bottom right). Reproduced from Ref. [59], under the terms of CC BY-SA 3.0 license. © 2023 C. Kunzmann et al.

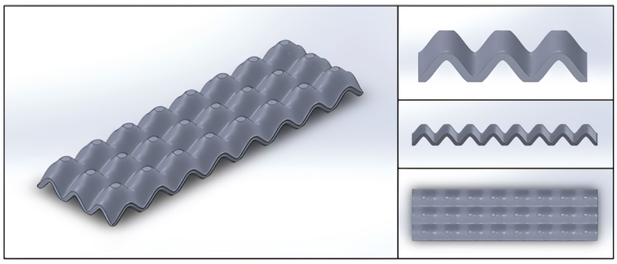

Fig. 10. Double-sine corrugated design: 3D view (left); unit cells (top right); side view (middle right); and top view (bottom right). Reproduced from Ref. [59], under the terms of CC BY-SA 3.0 license. © 2023 C. Kunzmann et al.

Inspired by these findings, efforts are underway to replicate this geometry as a foundational structure. The core design is influenced by the impact region of the peacock mantis shrimp [59].

10.3.4. Leaf design

As the preeminent group of organisms on our planet, plants have undergone extensive evolution over millions of years. This has resulted in a diverse array of functional biological surface structures, including leaves and grasses, which are exquisitely adapted to their environmental conditions. A leaf's primary function is to capture sunlight and initiate photosynthesis, a process essential for a plant's survival and the development of new leaves. Consequently, leaves must be highly resistant. They must support their own weight while occupying a confined space. Additionally, they must withstand external forces from rain and wind without sustaining structural damage. These demands closely align with the characteristics of sandwich composites. Leaves are excellent models for lightweight sandwich structures because they can cover large areas without requiring additional support, conserving weight and improving resistance. The regular corrugated folding patterns found in hornbeam and beech leaves, as illustrated in Figure 11, have attracted considerable attention from engineers for applications such as solar panels, lightweight satellite antennas, and folding deployable membranes, like tents and clothing. Studies have shown that folding increases stiffness and flexibility, reduces bulk and weight, enables structural transformation, and provides multifunctional design capabilities. Therefore, it is not surprising that certain leaf species have developed such structures to bolster their own resistance [59].

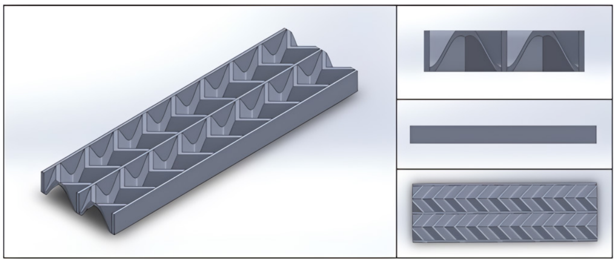

Fig. 11. Leaf design of multifunctional cellular structure: 3D view (left); unit cells (top right); side view (middle right); and top view (bottom right). The figure illustrates the geometric arrangement and structural features of the leaf-inspired design. Reproduced from Ref. [59], under the terms of CC BY-SA 3.0 license. © 2023 C. Kunzmann et al.

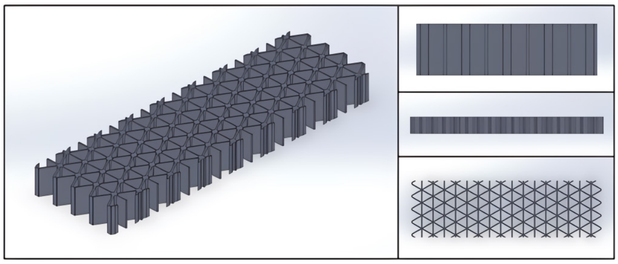

Fig. 12. Triangular bioinspired design for lightweight composites: 3D view (left); unit cells (top right); side view (middle right); and top view (bottom right). The triangular cellular topology demonstrates efficient load distribution and high stiffness-to-weight ratio, making it suitable for aerospace sandwich structures. Reproduced from Ref. [59], under the terms of CC BY-SA 3.0 license. © 2023 C. Kunzmann et al.

10.3.5. Triangular design

Rushes primarily thrive in regions susceptible to flooding. The central tissue of their rounded stems—which are essentially modified leaves—must possess a considerable amount of air space. This feature promotes the necessary air circulation for photosynthesis and allows the chlorophyll grains to encircle the cells. Each side of the triangle is interconnected with branches from another cell (Figure 12). At the contact points, the triangles expand slightly and merge with the transverse walls. This configuration is commonly known as "star tissue" due to its radiant appearance and extends throughout the elongated, cylindrical interior of the rush stem. The large voids facilitate efficient air circulation, and the hexagonal framework provides mutual reinforcement among cells and additional stiffness of leaf cavities. This structural design plays a crucial role in enhancing the buckling strength of the self-supporting system. Bending tests on fresh stalks revealed that star tissue contributes approximately 50% to bending stiffness and buckling resistance despite its minimal contribution to overall mass [59].

10.3.6. Urchin design

Sea urchins, particularly the species Tripnenestes gratilla, belong to the phylum Echinodermata. They are found in a wide range of marine habitats, including tropical and polar regions, as well as intertidal zones and depths of up to 5,000 meters. These creatures have existed for over 450 million years. The interconnected micropores in their skeletons play a crucial role in balancing internal and external pressures. This enables their shells to endure substantial water pressure, even in deep-sea conditions. Additionally, some sea urchin species inhabit areas with strong wave action. Sea urchin shells have evolved to function as exceptional natural armor underwater. They are capable of protecting against the tearing forces exerted by predators, supporting the weight of the coelom and exoskeleton, and meeting specific functional needs. These attributes have made sea urchin spines and plates subjects of interest in biomimetic research due to their lightweight yet stable properties. The design features a series of rotationally symmetrical hollow structures. While replicating the precise proportions of an average sea urchin was unachievable due to dimensional and volumetric constraints, examining how such a "hollow geometry" operates as a sandwich core remains intriguing. To increase the surface area for connections to cover plates and other hollow structures, the sides were trimmed accordingly. Additionally, due to the specified length, the ends of the two pairs had to be truncated at the edges, resulting in a slightly altered core structure (Figure 13) [59].

10.3.7. Venus design

Siliceous sponge spicules have attracted considerable interest due to their intricate, hierarchical structure; species-specific, nanoscale details; fracture-resistant

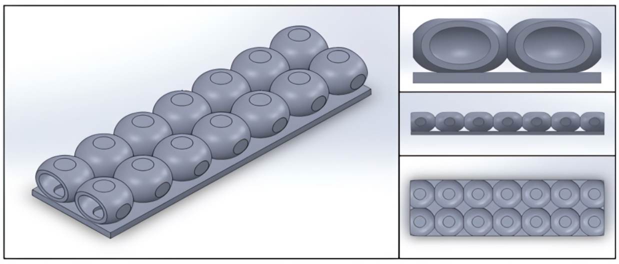

Fig. 13. Urchin design for composite sandwich structures: 3D view (left); unit cells (top right); side view (middle right); and top view (bottom right). The bioinspired geometry, derived from sea urchin morphology, illustrates a radial cellular pattern that enhances energy absorption and structural stability in lightweight composites. Reproduced from Ref. [59], under the terms of CC BY-SA 3.0 license. © 2023 C. Kunzmann et al.

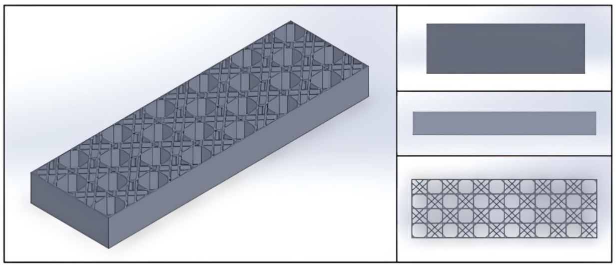

Fig. 14. Venus design for composite structures: 3D view (left); unit cells (top right); side view (middle right); and top view (bottom right). The geometry is adapted from natural Venus forms, demonstrating curved and periodic cellular patterns that improve stiffness and energy absorption in lightweight sandwich composites. Reproduced from Ref. [59], under the terms of CC BY-SA 3.0 license. © 2023 C. Kunzmann et al.

mechanical properties; and relatively fast biosynthesis rates. These spicules serve as model systems for studying bio-silica nanofabrication and translating fundamental mechanisms into the creation of new nanostructured materials and devices for advanced applications. The Venus flower basket sponge has an exceptionally beautiful and complex outer skeleton. It is distinguished by a cylindrical, lattice-like structure that encompasses at least six hierarchical levels ranging from nanometers to centimeters. These spicules create a locally quadrate, globally cylindrical skeletal lattice that serves as the framework for additional skeletal components. The structural intricacy of the glass skeleton demonstrates nature's ability to strengthen inherently weak materials. The mechanical stability of this design stems from the hierarchical assembly of glass constituents spanning from the nanoscale to the macroscopic scale. This structure can be viewed as a paradigm in mechanical engineering because the various hierarchical levels within the sponge skeleton utilize essential construction strategies, such as laminated structures, fiber-reinforced composites, and diagonally reinforced square-grid cells. Diagonal reinforcements enable the basic square grid skeleton to withstand bending, shear, and torsion loads arising from ocean currents or interactions with surrounding organisms, such as crustaceans (Figure 14) [59].

11. DESIGN AND MANUFACTURING PROBLEMS

A high-velocity impact event is typically fully extinguished in less than five milliseconds. The generation of internal heat is a consequence of the conversion of the projectile's kinetic energy (KE) and contact friction. The internal fracture energy (IE) is stored entirely within the embedded composite structure [4].

The airframe constitutes a pivotal component of an aircraft. During the course of flight operations, the aircraft is subjected to a multitude of complex loads and environmental influences, rendering it vulnerable to defects such as dents, cracks, corrosion, and others. Among these defects, water ingress into the honeycomb structures of an aircraft is of particular concern due to its potential to cause structural degradation and even catastrophic failure. Presently, a variety of methodologies are employed to detect water accumulation on the aircraft skin. The following methods are included: the ultrasonic method, the resistance method, the capacitance method, and the X-ray method, among others [61].

Conventional aircraft employ distinct flight control surfaces to navigate during flight. Gaps and discontinuities in these control surfaces generate drag, thereby reducing aerodynamics and power efficiency. The objective of morphing technology is to substitute conventional wings with advanced wings that possess the capability to modify their configuration in order to regulate the aircraft with the least possible drag [28].

These applications include components such as rudders, flaps, elevators, wings/tail trailing edges, landing gear compartment doors, APU compartment doors, and radar covers, among others [16].

Atmospheric icing poses a significant threat to aviation safety. During flight, supercooled water droplets found in clouds can collide with aircraft surfaces, leading to the formation of ice. This ice accumulation alters the geometry of the airfoil, which in turn negatively impacts the aerodynamic efficiency of the wing. Furthermore, the formation of ice in air inlet protection grids has been demonstrated to enhance fuel consumption and energy dissipation. In order to address the performance and safety issues associated with icing, the adoption of ice protection systems is essential. Thermal systems represent the predominant method employed for ice protection in large commercial jets. Presently, the Boeing© 787 is the sole commercial aircraft that is equipped with an electrothermal de-icing system that utilizes thermoelectric heating mats for surface protection. However, this technology is known for its high energy demands. Recent studies have focused on optimizing heat flux distribution to enhance the efficiency of electrothermal ice protection systems, thereby significantly reducing power usage. Additionally, investigations have explored the combination of electrothermal systems with glass fiber substrates, which allow for greater elastic energy storage within the ice layer compared to metal substrates. This phenomenon can be quantitatively evaluated using the ratio of elastic energy stored in the ice layer to the total elastic energy of the system (E_{ice} / E_{total}), which provides a measure of how efficiently the substrate and actuator combination mitigates ice-induced stresses. A promising strategy to mitigate parasitic bending caused by piezoelectric actuators involves integrating CFRPs with soft piezoceramics, which exhibit a higher relative ice ratio. It is imperative to employ a smaller relative ice ratio to ensure an average ratio that remains commensurate with the ice ratio [62].

Lightweight aerospace structures and power generation structures, including wind turbines, are designed with protected external layers and certified to withstand severe weather events, such as lightning strikes. During such events, high currents are known to flow through the structural shielding, with the potential to induce significant impacts on the supporting composite materials and to reach or puncture pressure vessels. According to the manufacturer, Airbus, lightning strikes every aircraft in service one to two times per year. As the aircraft traverses the atmosphere in proximity to cumulonimbus formations, the voltage gradient necessary for the initiation of a lightning arc is diminished, thereby precipitating an electrical discharge that would not have otherwise occurred [63].

Lightweight aerospace structures employed in the generation of energy, such as those utilized in wind turbines, are endowed with external protection layers that have been demonstrated to withstand inclement meteorological conditions, including lightning strikes. In such conditions, substantial electrical currents are known to pass through the structural protection, causing considerable damage to the underlying composite material. This may potentially compromise the structural integrity of pressure vessels. According to Airbus, lightning strikes every aircraft once or even twice per year. In the vicinity of cumulonimbus clouds, the voltage gradient necessary for the formation of lightning arcs is diminished, thereby facilitating electrical discharges that would not otherwise occur under different circumstances. Conventionally, metallic structures composed of wings and fuselages have effectively diverted lightning currents, thereby mitigating the risk of aircraft damage from lightning strikes. Historically, robust metallic structures have been the primary means of accomplishing this objective. Nevertheless, advanced composites, with their enhanced performance benefits, have increasingly replaced metals and have become an essential feature of the aerospace industry. For instance, composites comprise 50% of the structural weight of the Boeing© 787 Dreamliner. Despite the numerous advantages offered by composites in comparison to metals, their reduced electrical conductivity renders them more susceptible to damage caused by lightning. In the absence of adequate lightning protection, the Joule effect can generate high resistive heat, which has the potential to compromise structural integrity, reduce mechanical performance, or compromise flight safety. Compressive failures within honeycomb sandwich panel specimens exposed to lightning strikes predominantly occurred along the outer skin, while the unprotected specimen primarily failed at the central part of the panel [17].

A significant challenge in this field pertains to the flutter phenomenon, an aeroelastic instability that can lead to catastrophic consequences if not properly managed. Flutter manifests when aerodynamic forces interact with the natural modes of vibration of a structure, resulting in self-excited oscillations that can rapidly increase in amplitude. This phenomenon has the potential to induce substantial structural damage or even result in the complete failure of the structure. This phenomenon poses a significant threat to the safety and operational efficacy of flying vehicles. Consequently, maximizing the flutter speed—defined as the critical speed beyond which flutter occurs—is imperative in the context of aerospace design. Structures, particularly those designed for control surfaces such as fins and wings, are of paramount importance in the field of aeronautics. The customization of fiber orientation and stacking sequences within the sheets enables engineers to adjust mechanical properties such as stiffness and strength, which directly impact the flapping characteristics of the structure [64].

The provision of aerospace maintenance, repair, and overhaul (MRO) services is of paramount importance in ensuring the safe and certified operation of commercial aircraft. In the UK alone, the demand for these services generates an estimated annual turnover of £15 billion, and with the rapid growth in the number of commercial flights each year, this value is projected to rise. A critical structural element employed in aircraft surfaces is the sandwich panel, which comprises two outer layers composed of CFRP and an inner core consisting of aluminum honeycomb. During routine aircraft maintenance, various objects can impact the surface, including bird strikes and collisions with ground vehicles or equipment, which can lead to damage to the sandwich structure. The mechanical damage sustained by the panel is classified as follows: Debonding, defined as the separation of the core from the skin over a substantial portion of the panel, occurs due to the presence of high shear stresses at the interface and the impact-induced effects. Although the skin and core may still be in contact because the surrounding panel remains intact, this discontinuity typically results in a thin void and a decrease in material strength. Delamination is a potential concern within either of the sandwich skins, arising from the effects of shear stresses or impacts. This process entails the separation of two or more layers of CFRP that collectively constitute the skin. As with dis-bonds, the presence of a thin void is to be expected, and this will be accompanied by a loss of structural strength. The term "crushed core" is used to describe the compression of the aluminum honeycomb in one or more cells due to an external impact. A range of engine oils, lubricants for mechanical components, and fuels can migrate from their designated areas into the voids within the honeycomb structure through flow paths during standard aircraft operations. These paths traverse the porous regions of the sandwich panel skin or navigate through mechanical defects. In practice, the prevention of oil ingress poses a significant challenge, even for robust designs. Consequently, aircraft sandwich panel structures are often removed for routine maintenance and undergo "drying" cycles. The component is exposed to an elevated temperature of 80 °F within a vacuum environment to ensure the effective extraction of oil contaminants into a specialized porous collection medium. Contaminants have been observed to accumulate over a period of several months, while the drying cycle typically lasts less than two hours. In the event of dis-bonding and delamination, the affected skin sections are meticulously removed, along with the adjacent areas, to ensure the complete removal of damaged tissue. Subsequent to this procedure, new material is introduced to replace the skin and/or core. The entire sandwich panel must undergo vacuum sealing and be subsequently placed in an autoclave. Subsequently, the panel is subjected to a uniform pressure of 7 bar, applied through compressed nitrogen gas, to the surface of the component. The pressure within the autoclave during the curing process prevents the formation of voids and expels moisture and volatiles from the CFRP. The aerospace MRO industry employs two types of strategies for defect detection: inspection and testing. Testing processes are subject to stringent safety standards that have been established by International Aviation Safety Authorities. For instance, the EASA, the principal organization for safety compliance, oversees approved national organizations within the European Union that monitor MRO service operators. These authorities delineate the acceptable methods for testing components deemed critical to the safe operation of aircraft, such as airframe structures or engine mounting frames. Inspection procedures are governed by a series of safety standards that pertain to components deemed less critical for the safe functioning of aircraft. For instance, sandwich panels are utilized as protective surfaces for various components. Although it is imperative to minimize the occurrence of faults across all structures, a fault that arises during flight within a component subject to inspection protocols does not result in catastrophic consequences. The manual acoustic tap inspection is a widely accepted industry technique for detecting dis-bonds, delaminations, and crushed cores. A qualified MRO operator utilizes a testing hammer to delicately tap the surface of the sandwich panel at regular intervals. The presence of defects beneath the surface of the material results in a "duller" sound compared to surfaces without defects. This is due to the dampening effect on the acoustic resonance of the material's sandwich structure. This method is labor-intensive and contingent upon the operator's proficiency in discerning defective from normal areas. Potential defect locations are marked directly on the structure for subsequent repair once the drying cycles have been finalized [65].

Honeycomb sandwich composites (HSCs) may develop defects or damage (such as debonding, collapse, skin delamination, ponding, or impact damage) during the preparation process or prolonged operation in a challenging environment. The most prevalent defect is debonding, which occurs between the skin and the adhesive layer, and between the adhesive layer and the honeycomb core. These defects are typically small, discontinuous, and relatively concealed. As a result, HSCs exhibit no symptoms prior to failure. Nevertheless, they can abruptly deteriorate due to external impacts or internal stresses, which poses a significant threat to the structural integrity and severely impacts the normal functionality of the associated components [66].

Nevertheless, fluctuating environmental conditions and delamination of surface coatings during operation easily cause liquid to enter. Generally, a minor degree of liquid ingress is acceptable. However, certain hydraulic oils have the potential to cause significant mechanical failure in critical components. In the context of wave-transparent GFRP honeycomb structures, such as radomes, water ingress can severely impair wave-transparent functionality. Therefore, identifying and categorizing liquid ingress in honeycomb structures is crucial in both the manufacturing process and operational service [67].

Water ingression poses a significant challenge in honeycomb composite structures, potentially leading to severe structural failures. In the aviation sector, these materials are extensively utilized in the production of essential aircraft components, including the fuselage, wings, and flight control surfaces. The failure of such structures would have catastrophic consequences, making it imperative to detect water accumulation at the earliest stages of any defect. In order to maintain its reputation as the safest mode of transportation, the aviation industry must implement aircraft maintenance programs that are regulated, dependable, and continuous. Non-destructive testing techniques are frequently employed in such scenarios. These assessments are meticulously designed to inspect the airframe and engine components for any damage or indications of damage initiation, while preserving the original structural integrity. In the contemporary era, there has been a notable shift in the materials used to construct aircraft structures. Specifically, composite materials, particularly honeycomb composites, have become the preferred choice due to their exceptional strength-to-weight ratio and resistance to corrosion. This paradigm shift is evident in the design of crucial components such as the fuselage, wings, and flight control surfaces. Common problems associated with composite structures include debonding, delamination, cracks, dents, burns from lightning strikes, and water ingressions, all of which are prevalent issues. Despite the presence of voids resulting from damage or those created during prior repairs, as well as loosened fasteners and cracks stemming from material failures, atmospheric moisture infiltrates the honeycomb structure of the composite material. This infiltrated water, influenced by altitude variations during flights, undergoes thermal expansion and contraction, which generates undesirable stresses within the structure. These stresses can lead to debonding, delamination, and corrosion of the composite material. Moreover, water ingress has been demonstrated to be deleterious to the efficacy of composite repair processes, including composite curing. The identification of water within honeycomb structures can be facilitated by the implementation of several non-destructive testing methods, including tap testing, ultrasonic inspection, radiography, and thermography. Among the various methods evaluated, the most effective approach involved capturing an image during the cooling phase. In this technique, heating is applied for a brief period, followed by imaging during the subsequent cooling process. The resulting image exhibits enhanced contrast, as the honeycomb structure demonstrates a superior heat diffusion rate compared to water [68].

A carbon fiber-reinforced polymer (CFRP) laminate that exhibits substantial anisotropy comprises a sandwich structure. The core of this structure is positioned between the outer skins on both sides. This configuration provides exceptional strength-to-weight ratios and is predominantly utilized in the aviation sector, particularly in applications such as aircraft flooring, doors, wing flaps, and rudders; as well as in automobiles and building panels. It is utilized as a honeycomb sandwich panel, wherein a CFRP skin is adhered to a honeycomb core. Defects within the sandwich structure can arise from various factors. It has been observed that aircraft frequently sustain damage subsequent to the commencement of operations. Honeycomb composites, being hollow structural materials, are particularly vulnerable to liquid intrusion. Common forms of liquid intrusion include water and hydraulic oil, which may result from inadequate sealing or damage to the skin. In order to mitigate the risk of severe damage caused by the presence of water in the aircraft structure, significant interest has been expressed in various non-destructive testing methods, and research efforts have been directed towards this area. In recent years, a variety of techniques have been employed to assess the integrity of honeycomb structures, including ultrasonic testing, radiological and neutron radiography, helium mass spectrometer leak detection, and hot water leak testing. These methods have proven effective in detecting and identifying water ingress within these structures. Nonetheless, ultrasonic inspection is a time-consuming process due to the necessity of meticulous, point-by-point examination, which consequently leads to diminished productivity. Moreover, the utilization of radiation and neutron radiographic techniques is seldom implemented in clinical practice due to the inherent challenges associated with size, the necessity for double-sided installation, and the stringent radiation safety measures that must be adhered to. The process of testing for hot water leaks entails the potential for water infiltration into components. Conversely, helium mass spectrometry methods are often costly and require a high degree of operator expertise. In the 1990s, pulsed thermography was employed to identify corrosion and detachment in B737 testbed aircraft. Since that time, a range of infrared thermography techniques and data processing algorithms have been developed and utilized for the detection of water ingress in honeycomb sandwich composites [69].

12.CONCLUSION

The incorporation of composite materials and honeycomb sandwich structures has revolutionized the design and performance of aerospace systems. With their superior mechanical properties and adaptability, these materials address key challenges in reducing structural weight while maintaining or enhancing strength and reliability. Their use spans from rotor blades and wing components to engine casings and radar-absorbing panels. Notably, materials such as SiC-based ceramic matrix composites and carbon fiber-reinforced polymers have demonstrated exceptional capabilities under extreme conditions, including high-temperature and high-velocity impact environments. Furthermore, advances in 3D printing and additive manufacturing have unlocked new possibilities for producing complex geometries with optimized stiffness and energy absorption (Figure 15). Despite their benefits, composite and honeycomb structures are not without limitations. Issues such as delamination, moisture ingress, lightning vulnerability, and flutter phenomena pose significant design and maintenance challenges. However, ongoing research is addressing these limitations through enhanced material characterization, novel structural topologies, and hybrid manufacturing methods. As aerospace engineering continues to evolve, the integration of smart structures,

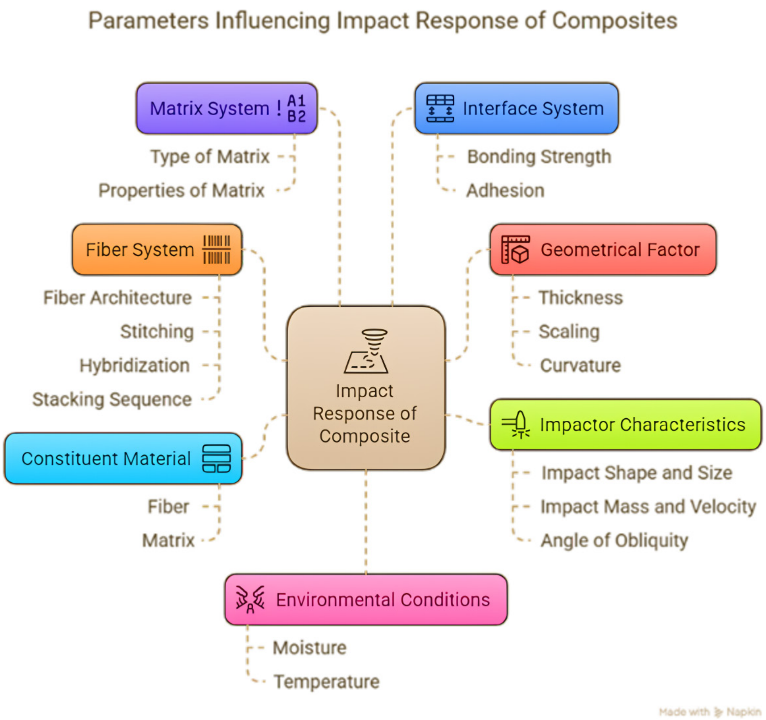

Fig. 15. Main parameters affecting the impact response of composites.

bioinspired morphing mechanisms, and high-performance composites is expected to play a crucial role in shaping the next generation of lightweight, adaptive, and resilient aircraft.

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Современные многофункциональные композитные клеточные структуры: инновации и влияние в аэрокосмическом машиностроении

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Аннотация. В последние годы аэрокосмическая промышленность все активнее внедряет композиционные материалы и сотовые конструкции для решения задач создания легких, высокоэффективных и энергоэффективных конструкций. Эти достижения привели к замене традиционных металлических компонентов на волокнистые полимерные материалы, керамические матричные композиты и усовершенствованные сотовые наполнители в критически важных структурных элементах, таких как крылья, обшивки фюзеляжа и лопасти роторов. Сотовые сэндвич-панели благодаря их превосходному соотношению жесткости и массы, а также способности поглощать энергию, широко применяются как в гражданской, так и в военной авиации. В данной работе исследуются механические характеристики, области применения в конструкции и технологии производства этих структур. Особое внимание уделяется интеграции сотовых ячеек с градиентной плотностью, радиопоглощающих материалов и технологий адаптивно-перестраиваемой геометрии крыла, которые повышают аэродинамическую эффективность и маскировочные свойства. В работе также рассматриваются актуальные проблемы, такие как устойчивость к ударам, уязвимость при ударах молнии, явления флаттера и проникновение влаги, способные нарушить целостность конструкции. Более того, исследование охватывает последние инновации в области аддитивного производства и био-вдохновленных дизайнов, поддерживающих разработку сложных геометрий и адаптивных конструкций. Эта статья подготовлена как всесторонний обзор, направленный на обобщение и критическую оценку современных достижений в области композиционных материалов и многофункциональных ячеистых структур в авиационно-космической технике.

Ключевые слова: сотовая структура; композиционная конструкция; аэродинамическая эффективность; сэндвич-панель; волокнистые полимерные материалы