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Article

Biomimetics Design of Sandwich-Structured Composites

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Abstract: In the context of energy efficiency and resource scarcity, lightweight construction has gained significant importance. Composite materials, particularly sandwich structures, have emerged as a key area within this field, finding numerous applications in various industries. The exceptional strength-to-weight ratio and the stiffness-to-weight ratio of sandwich structures allow the reduction in mass in components and structures without compromising strength. Among the widely used core designs, the honeycomb pattern, inspired by bee nests, has been extensively employed in the aviation and aerospace industry due to its lightweight and high resistance. The hexagonal cells of the honeycomb structure provide a dense arrangement, enhancing stiffness while reducing weight. However, nature offers a multitude of other structures that have evolved over time and hold great potential for lightweight construction. This paper focuses on the development, modeling, simulation, and testing of lightweight sandwich composites inspired by biological models, following the principles of biomimetics. Initially, natural and resilient design templates are researched and abstracted to create finished core structures. Numerical analysis is then employed to evaluate the structural and mechanical performance of these structures. The most promising designs are subsequently fabricated using 3D printing technology and subjected to three-point bending tests. Carbon-fiber-reinforced nylon filament was used for printing the face sheets, while polylactic acid (PLA+) was used as the core material. A honeycomb-core composite is also simulated and tested for comparative purposes, as it represents an established design in the market. Key properties such as stiffness, load-bearing capacity, and flexibility are assessed to determine the potential of the new core geometries. Several designs demonstrated improved characteristics compared to the honeycomb design, with the developed structures exhibiting a 38% increase in stiffness and an 18% enhancement in maximum load-bearing capacity.

Keywords: bio-inspired core; biomimetics; lightweight panel; sandwich composites

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1. Introduction

Biomimetics, the science of emulating and applying principles observed in nature to solve engineering challenges, has gained significant attention and recognition in recent years. This approach has proven to be a valuable source of inspiration for the design and development of innovative materials and structures. In nature, organisms have evolved over millions of years to develop sophisticated structures that provide strength, efficiency, and adaptability. By studying and understanding these natural structures, researchers and engineers have been able to design bio-inspired materials and structures that mimic the advantageous properties found in nature [1–5]. This field of research, often referred to as biomimetics or bio-inspired engineering, offers tremendous potential for developing novel and optimized sandwich-structured composites.

One area where biomimetics can show great promise is in the design of sandwich-structured composites, which are composite materials consisting of two thin outer layers (face sheets) and a thick, lightweight core material in between [6]. The concept of sandwich structures has been widely adopted in various industries due to their exceptional mechanical properties, such as high strength, stiffness, and energy absorption capabilities while maintaining a relatively low weight. These materials find applications in diverse fields, including aerospace, automotive, marine, and civil engineering, where lightweight and high-performance materials are of utmost importance [7].

The motivation behind pursuing biomimetic design approaches in sandwich composites lies in the quest for improved performance and efficiency. Nature has provided numerous examples of efficient and lightweight structures that have evolved over millions of years of natural selection. These structures have evolved to withstand different types of mechanical stresses and environmental conditions, providing inspiration for the development of high-performance composite materials.

One prominent example of a natural structure with remarkable mechanical properties is the honeycomb structure found in bee colonies. The hexagonal arrangement of individual cells in the honeycomb provides an optimal combination of strength and weight efficiency, making it a highly effective design for load-bearing structures. The honeycomb core geometry has been extensively utilized in aerospace technology, military applications, and other industries that demand lightweight and strong materials [1]. Its success has motivated researchers to explore other natural structures for potential biomimetic designs [8].

Although the honeycomb core has emerged as a highly successful and widely used design in various industries, it is important to recognize that there are other biomimetic designs that hold the potential for even greater efficiency and performance in sandwich-structured composites. In line with the concept of biomimicry, this paper explores the development, modeling, simulation, and testing of lightweight sandwich composites. Organic structures with extraordinary mechanical properties and low weight in their natural ecosystems served as models for various core geometries. The designed sandwich panels are subjected to numerical analysis via a three-point bending simulation. Promising designs are then fabricated using 3D printing technology and evaluated using physical experiments. To assess the efficiency of the geometries, a reference geometry using the proven honeycomb design is also created under identical conditions.

By exploring alternative biomimetic designs, we aim to unlock new possibilities and further enhance the mechanical properties of sandwich composites. Nature provides a wealth of inspiration, ranging from the hierarchical organization of nacre to the fibrous architectures found in plant stems and the cellular structures observed in biological tissues. By studying and emulating these natural designs, it is possible to develop novel core structures with superior mechanical characteristics. The current paper proposes novel biomimetic designs for sandwich structures, introducing a fresh perspective in the field of lightweight construction. While the honeycomb pattern has been widely utilized, inspired by bee nests, this manuscript explores alternative design templates found in nature. By leveraging the principles of biomimetics, this paper presents the results of modeling, simulation, and testing to develop and evaluate new lightweight sandwich composites. To the best of our knowledge, the proposed biomimetic core designs for the sandwich structures have not been reported before.

2. Biomimetics Designs

This section presents the methodology employed for generating biomimetic core geometries in sandwich panels. The primary objective in designing sandwich structures is to reduce component weight while maintaining equivalent stiffness [9]. Emphasis is placed on mechanical properties such as stiffness, energy absorption capacity, and flexural modulus. Therefore, it is crucial to identify biostructures that naturally exhibit resistance to external mechanical loads, including weather influences, streaming forces, and predatory species. These biostructures may involve features such as exoskeletons or shells. Furthermore, it is essential to select structures that possess a symmetrical pattern capable of uniformly covering a surface. Failure to achieve this symmetry would result in a sandwich composite with spatially varying mechanical properties.

The research conducted in this study adhered to these specifications. Once potential biological models were identified, they were modified to meet the requirements of a sandwich composite. The core designs developed in this study were abstracted from suitable biostructures and directly generated using the CAD software SolidWorks. Subsequently, an assembly was created, integrating the core structures with the cover plates.

To facilitate the comparison of the mechanical properties among the developed composite structures, it was necessary to model them with consistent dimensions and weight. The panels in this research were standardized to a width of 30 mm and a length of 100 mm. The core height was set at 10 mm, while the face layer had a height of 2 mm.

Achieving consistent weight across different core designs proved more challenging, given the significant geometric variations. Thus, weight control was achieved via the comparison of volumes. A maximum deviation of 1% from the reference geometry (honeycomb design) was set as the criterion and iteratively adjusted for the other models. The reference geometry had a volume of 7201 mm^3 out of a potential volume of 30,000 mm^3, indicating that approximately 76% of the space between the surface layers was occupied by air.

2.1. Diatom Design

Diatoms, belonging to the class of unicellular algae, are marine microorganisms. They entered the plant kingdom relatively late in evolution using a unique process. Researchers speculate that diatoms are secondary endosymbionts, meaning their ancestors engulfed another eukaryote, resulting in the formation of a four-layered membrane around the chloroplasts obtained through this act of symbiosis [10]. Today, diatoms are found in oceans, freshwater, and even soil worldwide. The question arises: Why have diatoms been exceptionally successful? Many scientists attribute their success to the presence of silicified cell walls, known as frustules, which consist of two shells with remarkable shapes and intricate patterns [11]. These frustules provide physical protection to the cell against mechanical challenges. The silicates present in their skeletons are obtained via nutrient intake, and the frustules serve as protective outer covering against predators, providing them with exceptional stability. The optimal performance characteristics are achieved by combining the highest level of protection with minimal material consumption. Figure 1 illustrates an image of an Actinoptychus, along with a virtual reconstruction used for stress analysis. Measurements of diatom exoskeleton strength revealed the substantial forces required to break them down [12]. The geometry exhibits high tensile and compressive strength and possesses an elasticity modulus similar to that of solid bone. Additionally, the silicate structures display remarkably favorable stress distributions [12]. Diatoms achieve maximum stability with minimal material usage, aligning with the objectives of modern lightweight structures. The corrugated membrane and the porous substructure with the irregular arrangement are particularly noteworthy. The corrugation enhances the design's robustness against radial and circumferential loads. The overall structure resembles a stiffened, thin-walled structure, providing resistance to axial loads and combinations from all directions.

Figures 2 and 3 depict the sandwich core geometries inspired by and abstracted from the diatom exoskeleton. These designs feature the same corrugated pattern observed in the original structure, extending from the center to the edges. However, Figure 3 includes an increased number of stiffening waves, from three to six, to enhance toughness and produce a hexagonal pattern. This allows for the combination of multiple individual elements to create a large-scale structure. The two designs differ in the number of symmetry planes. Both structures, with volumes of 7253 mm^3 and 7277 mm^3, respectively, fall within the 1% tolerance limit compared to the reference geometry.

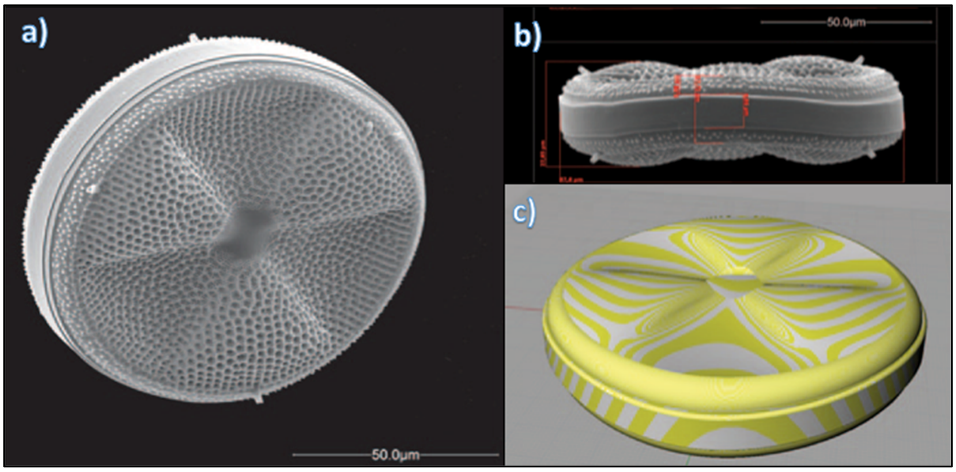

Figure 1. Recordings of an Actinoptychus and its shape reconstruction for the investigation of different stress situations [12].

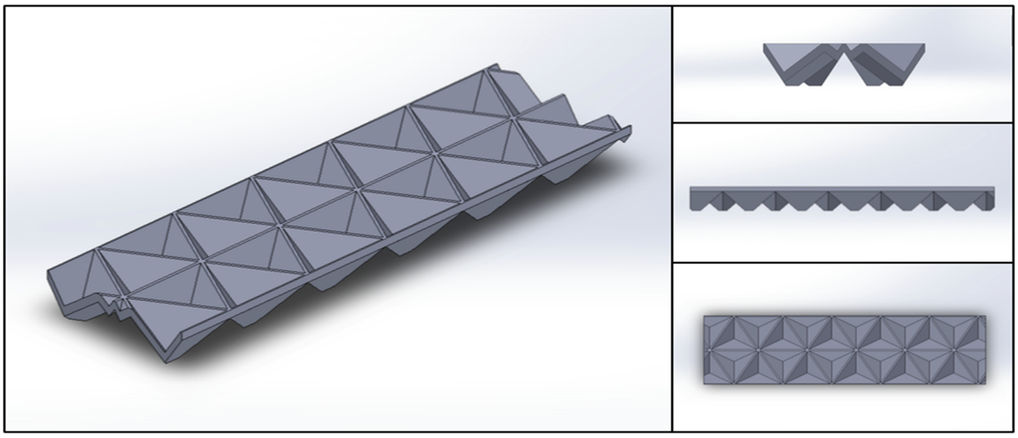

Figure 2. Diatom-Design 1 with two symmetric planes: 3D view (**left**); unit cells (**top right**); side view (**middle right**); and top view (**bottom right**).

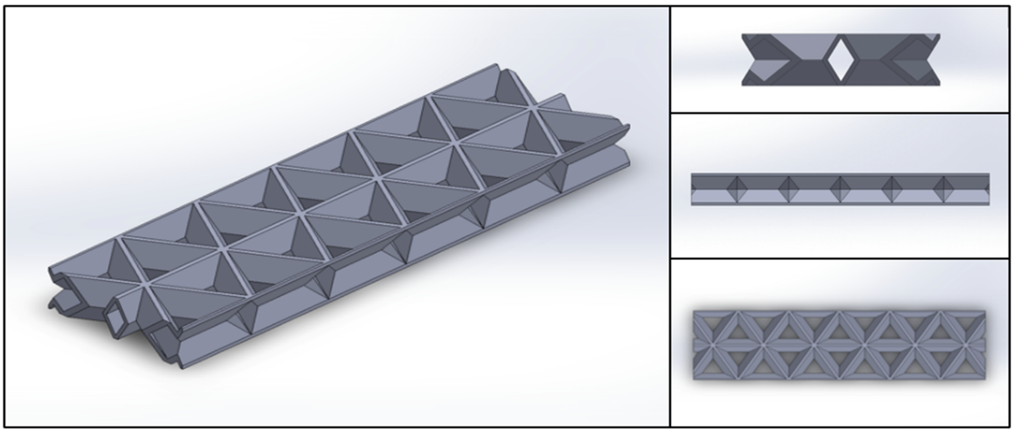

Figure 3. Diatom-Design 2 with three symmetric planes: 3D view (**left**); unit cells (**top right**); side view (**middle right**); and top view (**bottom right**).

2.2. Double-Helix Design

The double helix structure is an extraordinary geometrical arrangement found abundantly in nature. It manifests at both macroscopic and microscopic scales. Macroscopic helical structures can be observed in various organisms, such as shells, horns, plant tendrils, and sea pods [13]. The double helix configuration is a stable and hierarchical arrangement characterized by the continuous rotation of two single helical segments around the longitudinal axis [14].

Moreover, the exoskeletons of many arthropods, such as the American lobster (Homarus americanus) or the Japanese beetle (Popillia japonica), exhibit remarkable structural properties in terms of supporting their body weight and resisting external stresses [15]. These exoskeletons often share similar structural morphologies. They possess a multi-layered structure, and the orientation and patterns of the exoskeleton organization are fundamentally alike. Helical geometry is also evident at the microscopic level, indicating its high potential for structures with exceptional stiffness and strength, as reported by Chen et al. [15]. Figure 4 shows the hierarchical and helicoidal structures present in the exoskeletons of two distinct species, namely Homarus americanus (American lobster) and Popillia japonica (Japanese beetle). These organisms have evolved remarkable exoskeletons that exhibit intricate hierarchical arrangements and helicoidal patterns, offering insights into novel design principles for structural materials. The hierarchical structure refers to the multi-level organization found within the exoskeleton, where different length scales contribute to the overall mechanical properties. On the other hand, the helicoidal pattern refers to the spiral-like arrangements observed within certain regions of the exoskeleton, providing additional strength and toughness.

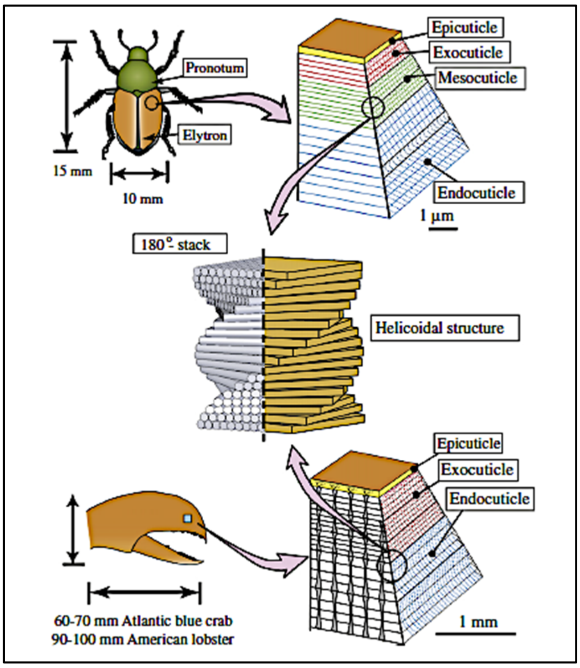

Figure 4. The hierarchical and helicoidal structures of the exoskeletons from Homarus americanus and Popillia japonica [15].

The prevalence of this helical form in nature can be attributed to its inherent properties, as the double-stranded nucleoid imparts greater mechanical stability. Consequently, this structure is now utilized for reinforcement in various fields. For instance, Shang et al. [14] employed it to significantly enhance the mechanical properties of carbon nanotubes. The twist in the helix substantially augments stability against bending or buckling, making this geometry particularly intriguing for implementation within sandwich cores. Chen et al. [15] explored the use of twisted arrangements in composite structures, demonstrating that this bio-inspired design exhibits significantly improved mechanical properties compared to conventional basic structures.

The core structure presented in this paper, as depicted in Figure 5, comprises individual plates that undergo a consistent 180-degree twist along the longitudinal axis. These plates are evenly distributed over the surface layers. With a volume of 7211 mm^3, this structure falls within the specified tolerance of 1% compared to the reference structure.

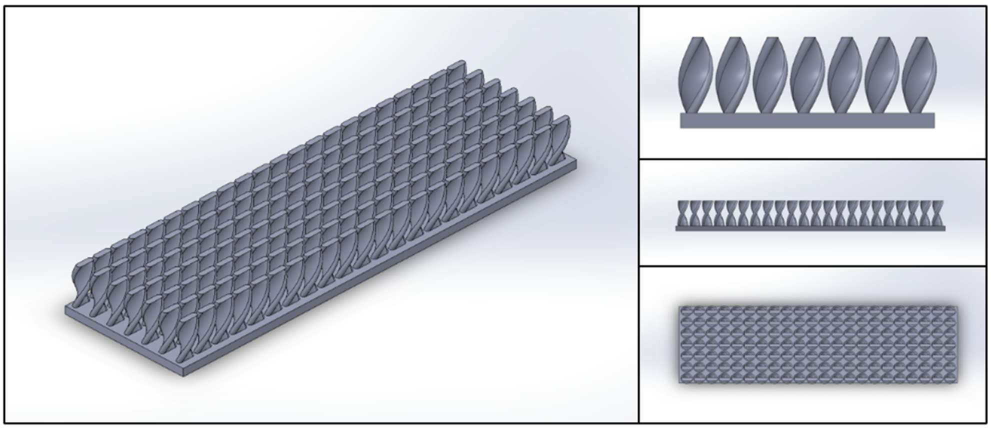

Figure 5. Double-helix Design: 3D view (**left**); unit cells (**top right**); side view (**middle right**); and top view (**bottom right**).

2.3. Double-Sin Corrugated Design

Stomatopods, as depicted in Figure 6, are crustaceans found in marine environments, inhabiting cavities and burrows in tropical reefs worldwide [16]. They are known for their highly aggressive nature and their ability to defend their burrows using a powerful raptorial appendage. The peacock mantis shrimp, a subspecies of stomatopod, possesses a heavily armored telson (known as the dactyl club) that can be unfolded and extended forward, similar to the striking appendage of a praying mantis. With this tool, as shown in Figure 6b, they hunt hard-shelled prey such as snails, shells, and crabs, delivering devastating strikes capable of breaking even the strongest defenses. To illustrate the striking power, it is worth noting that even small peacock mantis shrimps measuring 50 mm in length can break the walls of glass aquariums [16]. The dactyl strike of the peacock mantis shrimp is one of the most powerful and fastest impacting events observed in nature, achieving accelerations over 10,000 g and speeds of 23 m/s from a resting position [17]. These strikes generate forces of up to 1500 N and impose extreme stresses on the structure, yet the dactyl club can withstand them repeatedly without sustaining any damage. As a living fossil, this species has evolved over countless generations to adapt to these stresses and modify the microstructure of the dactyl club to possess exceptional strength, stiffness, and toughness.

The mechanical response of the dactyl club can be attributed to its structural composition. It is a multi-phase composite consisting of oriented crystalline hydroxyapatite, amorphous calcium phosphate, and carbonate, and a highly expanded helicoidal organization of the fibrillar organic matrix. These features provide several effective mechanisms for defense against catastrophic failure during high-energy strikes [17]. In addition to the suitable material properties, the structural orientation of the different layers plays a crucial role in ensuring the dactyl club's damage tolerance and impact resistance. Micro-computed tomographic imaging, as shown in Figure 6d, reveals the internal structure divided into an impact region and a periodic region. The impact region consists of a thin surface layer and a thick bulk component with an extremely ordered sinusoidal pattern. Yaraghi et al. [17] demonstrated using finite element simulations and physical tests that this structure is a key factor in the extraordinary resistance and strength of the dactyl club.

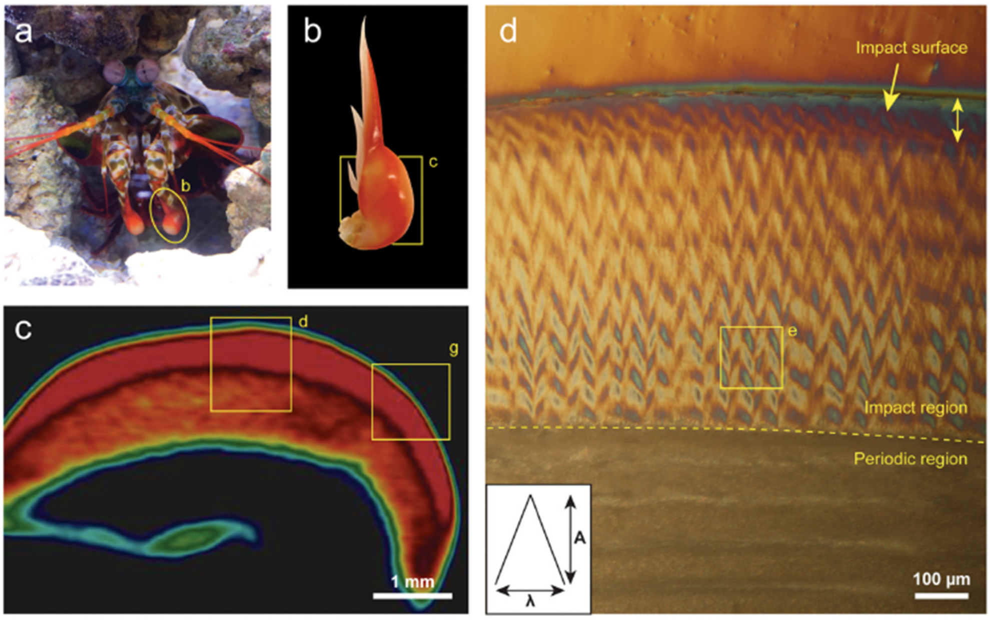

Figure 6. Morphological features of the stomatopod dactyl club. (**a**) Close-up of the anterior end of peacock mantis shrimp with a circle denoting the dactyl's striking appendage. (**b**) Separate image of the dactyl club. (**c**) CT scan of a sagittal selection as denoted in (**b**). (**d**) Micro-tomographic image highlighting the impact surface, the sinusoidal region, and the periodic region [17].

Inspired by these findings, an attempt is made to replicate this geometry as a core structure. The core design inspired by the impact region of the peacock mantis shrimp is depicted in Figure 7. The design is based on a "hilly landscape" generated by the fusion of sine equations in the x-direction and y-direction using CAD software. The challenge in this design is to minimize the respective curves at the ends of the sandwich composites to achieve uniform support. The equations used are described as follows:

$$f(x) = \sin\left(0.6281x - \frac{\pi}{2}\right) \tag{1}$$

$$f(y) = \sin\left(0.5025x - \frac{\pi}{2}\right) \tag{2}$$

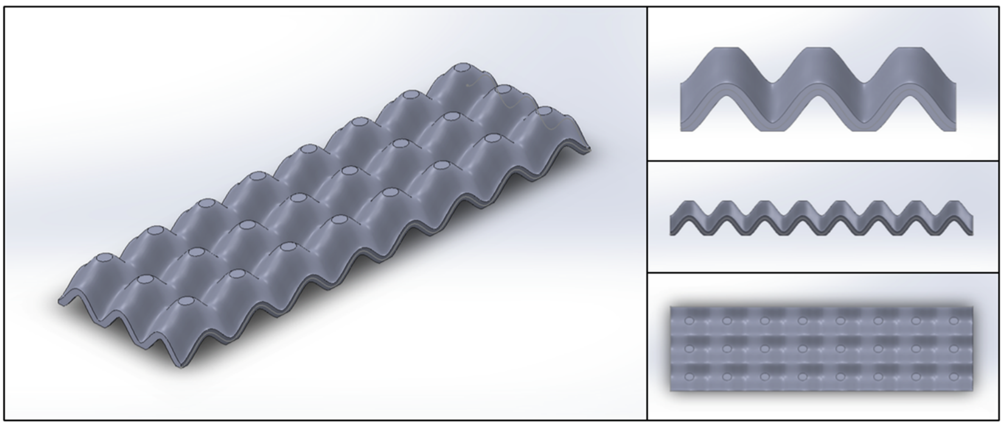

Figure 7. Double-sine corrugated Design: 3D view (**left**); unit cells (**top right**); side view (**middle right**); and top view (**bottom right**).

To increase the adhesion area, the upper and lower peaks are separated. The volume of this design is 7179 mm^3, which falls within the specified tolerance.

2.4. Leaf Design

Plants, as the dominant group of organisms on Earth, have evolved over millions of years to possess a wide variety of functional biological surface structures, such as leaves and grasses, that are perfectly adapted to their external conditions [18]. The primary function of a leaf is to absorb sunlight and initiate photosynthesis, which provides the basis for a plant's survival and the growth of new leaves. Therefore, leaves require a high degree of resistance. They must be able to support their own weight while occupying a limited area. Additionally, they need to withstand external forces caused by rain and wind without sustaining structural damage. These requirements closely resemble the properties of sandwich composites. Leaves are well-suited as models for lightweight sandwich structures because they can cover large areas without the need for additional external support structures, saving weight and enhancing resistance.

Some plant leaves exhibit folding or rolling even while they are still in the bud, maintaining this shape as they grow. The regular corrugated folding patterns observed in leaves of hornbeam or beech, as depicted in Figure 8, have garnered significant interest from engineers for various applications, including solar panels, lightweight satellite antennae, and the folding of deployable membranes like tents or clothes [19]. Research has shown that folding increases the stiffness and flexibility of materials, reduces bulk and weight, enables structural transformation, and provides design multifunctionality [20]. It is not surprising, therefore, that certain leaf species have evolved such structures to enhance their own resistance.

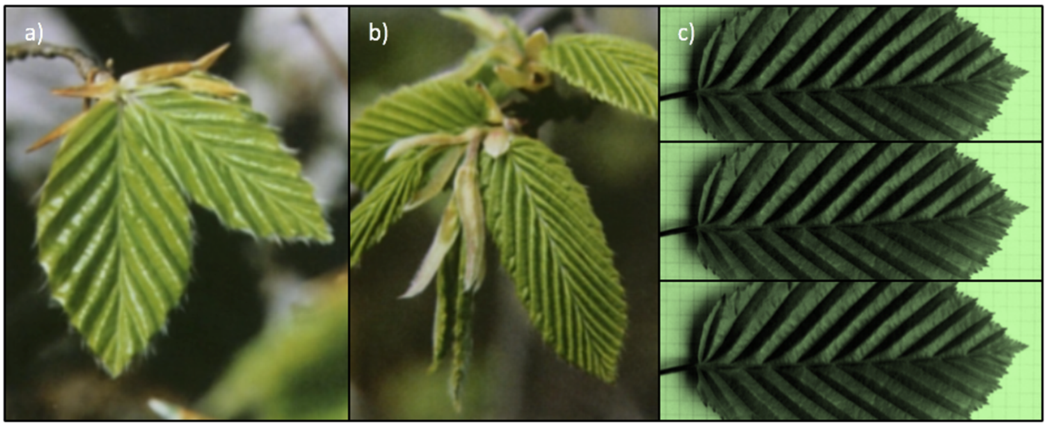

Figure 8. Corrugated leaves of (**a**) beech, (**b**) hornbeam, (**c**) Representation of adjacent beech leaves to visualize the aspired design structure [19].

As Vogel's study [21] on plants has demonstrated, some leaves, particularly those of monocots, utilize a slight longitudinal V-fold to achieve adequate flexural stiffness while maintaining low torsional stiffness. However, it is not only the corrugated leaf pattern that contributes to leaf resistance. The leaf central vane, also known as the midrib, is a crucial structural component for leaf mechanics. Studies on maize leaves, for example, have shown that the midrib greatly stiffens the leaf, especially in regions where bending moments are high [21]. Similar findings have been reported in other studies, indicating that the tissue with the highest resistance in leaves is consistently the midrib [22].

The bionic design of the core structure depicted in Figure 9 incorporates these two stabilizing characteristics of plant leaves. A solid beam structure is created, supported by a corrugated structure. The wave pattern runs at a 45-degree angle from a central beam, resembling the shape of an arrow and inspired by the arrangement of beech leaves shown in Figure 8c. To increase the adhesion area, the peaks of the folded structure are removed. The resulting design has a volume of 7245 mm^3, falling within the specified tolerance of 1%.

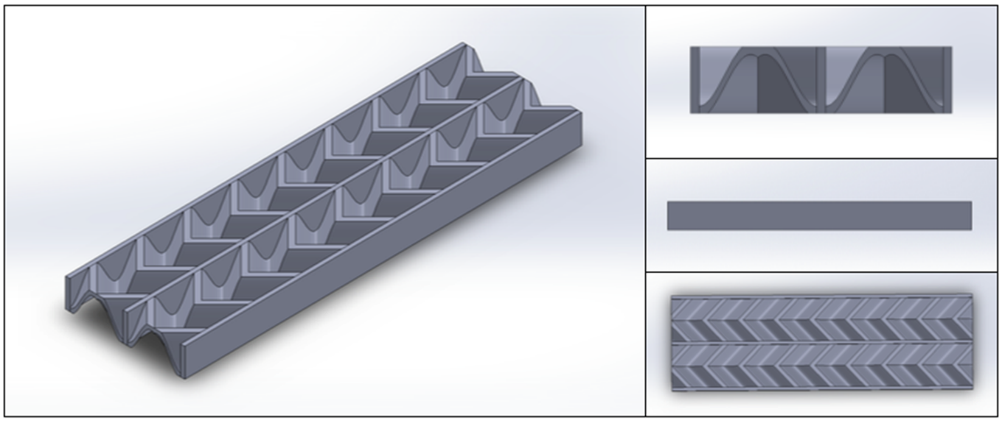

Figure 9. Leaf Design: 3D view (**left**); unit cells (**top right**); side view (**middle right**); and top view (**bottom right**).

2.5. Triangular Design

Hexagonal grids are a common occurrence in both nature and technology, often observed in structures such as the compound eyes of insects and the honeycombs built by bees and wasps. Hexagons are ideal for space-saving architectures as they close seamlessly, making efficient use of available space. The combination of hexagonal architecture and the inherent stability of equilateral triangles has evolved in the rushes of the Juncus genus (Figure 10) and has various advantages [23].

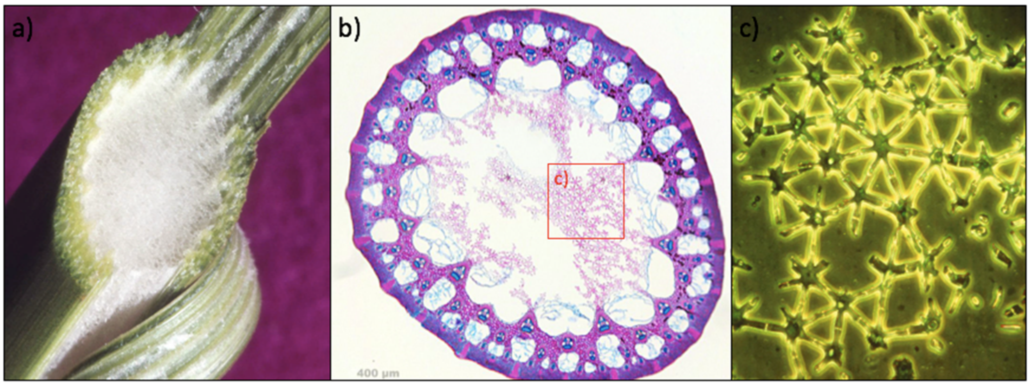

Figure 10. Structure of a rush stem (Juncus): (**a**) Broken rush stem, (**b**) Top view of enlarged (400 µm) colored rush stem, (**c**) Microscopic image of star tissue [23].

Rushes predominantly grow in areas prone to flooding. The inner tissue of their rounded stems, which are actually modified leaves, must contain a significant amount of air space. This facilitates the circulation of air necessary for photosynthesis and enables the chlorophyll grains to surround the cells [23]. As depicted in Figure 10c, the interior cells of the rush contain multiple outgrowths that connect with the outgrowths of neighboring cells to form more or less regular hexagonal grids. These hexagonal grids consist of equilateral triangles, where each side of the triangle is shared with another cell's branches. At the contact points, the triangles slightly widen and merge with the transverse walls. This arrangement, often referred to as "star tissue" due to its radiant nature, spans the entire elongated cylindrical interior of the rush stem. The large gaps allow easy air circulation, while the hexagonal network provides mutual stiffening between cells and additional stiffening of leaf cavities. This design contributes significantly to the buckling strength of the self-supporting system. Bending tests on fresh stalks demonstrated that the star tissue accounts for approximately 50% of the bending stiffness and buckling resistance despite contributing minimally to the overall mass. Nachtigall [12] describes this design as an "intelligent material" that achieves significant effects with strategically distributed masses. Thus, it represents a natural lightweight construction that achieves mechanical stability and resistance akin to the concept of sandwich composite construction.

The core structure depicted in Figure 11 was inspired by the star tissue of the rush. Each connecting point serves as the center and corner point within the hexagonal grid. To reduce notch stresses, radii were incorporated at these points. The equilateral triangles in this design have an edge length of 6 mm. The total volume of this sandwich core is 7253 mm^3.

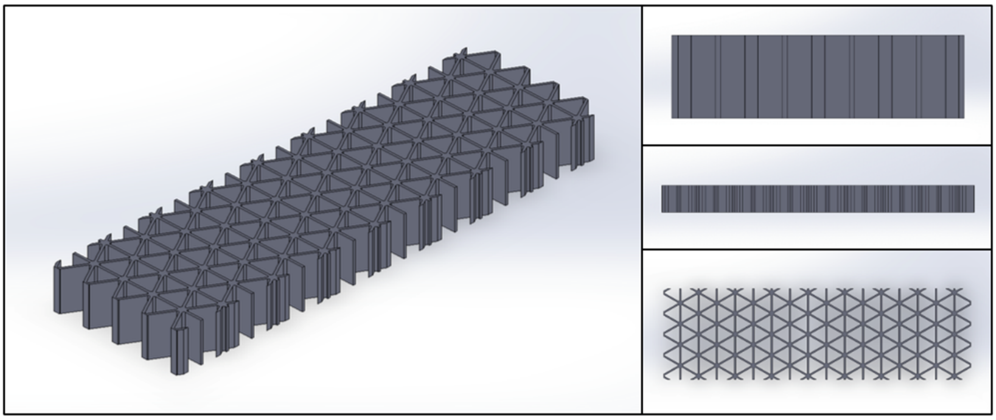

Figure 11. Triangular Design: 3D view (**left**); unit cells (**top right**); side view (**middle right**); and top view (**bottom right**).

2.6. Urchin Design

The ocean covers 71% of Earth's surface and is a vast reservoir of biological, chemical, mineral, space, and energy resources. More than 80% of Earth's living organisms, totaling over 40,000 different species, are found in the aquatic ecosystem, making it an endless source of scientific research [24]. Sea urchins, specifically the Tripnenstes gratilla species, are Echinodermata invertebrates that are widely distributed across various marine environments, ranging from tropical to polar regions and from intertidal zones to depths of 5000 m, and they have been in existence for over 450 million years [25]. Figure 12 depicts a living sea urchin and its skeleton. After removing the spines, the average diameter, height, and thickness of the inorganic skeleton are measured to be 8 cm, 4.5 cm, and 1.72 mm, respectively [26].

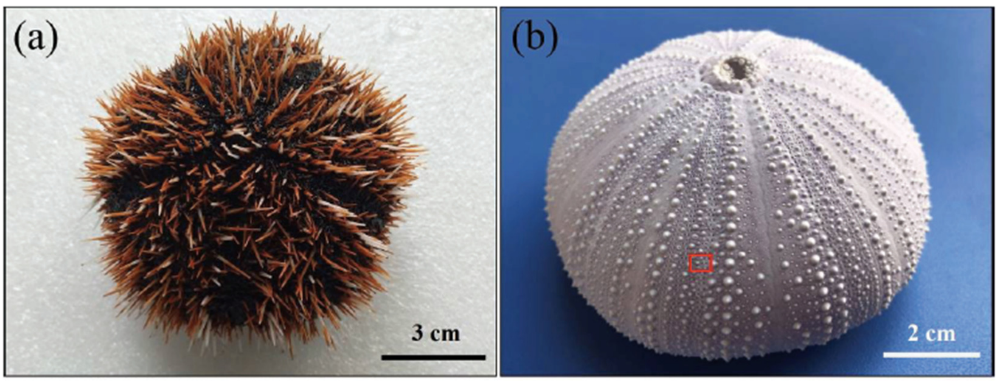

Figure 12. (**a**) A living body of a sea urchin; (**b**) Skeleton of a sea urchin [26].

The interconnected micron pores in the sea urchin's skeleton help balance the internal and external pressures, allowing the shell to withstand a significant portion of the water pressure even in deep-sea environments. Additionally, certain species of sea urchins prefer to inhabit areas with heavy wave action [26]. The shell of a sea urchin has evolved to serve as an excellent natural underwater protective armor, capable of defending against tearing forces from predators, supporting the weight of the coelom and exoskeleton, and fulfilling specific functional requirements. Due to these factors, sea urchin spines and plates have attracted interest in biomimetic research thanks to their lightweight material properties combined with inherent stability [27,28]. The structure developed via evolution to meet these requirements is comparable to sandwich composites and can serve as inspiration for lightweight core structures.

The core structure depicted in Figure 13 was inspired by the sea urchin's skeleton. The design consists of a series of rotationally symmetrical hollow bodies. Although it was not feasible to replicate the exact proportions of an average sea urchin due to the given dimensions and volumes, it is nonetheless fascinating to observe how such a "hollow geometry" functions as a sandwich core. To increase the surface area for connections to the cover plates and other hollow bodies, the sides were appropriately trimmed. Furthermore, due to the given length, it was necessary to remove the ends of the two pairs at the edges, resulting in a slightly modified core structure. The volume of this sandwich core design is 7203 mm^3, falling within the specified tolerance range.

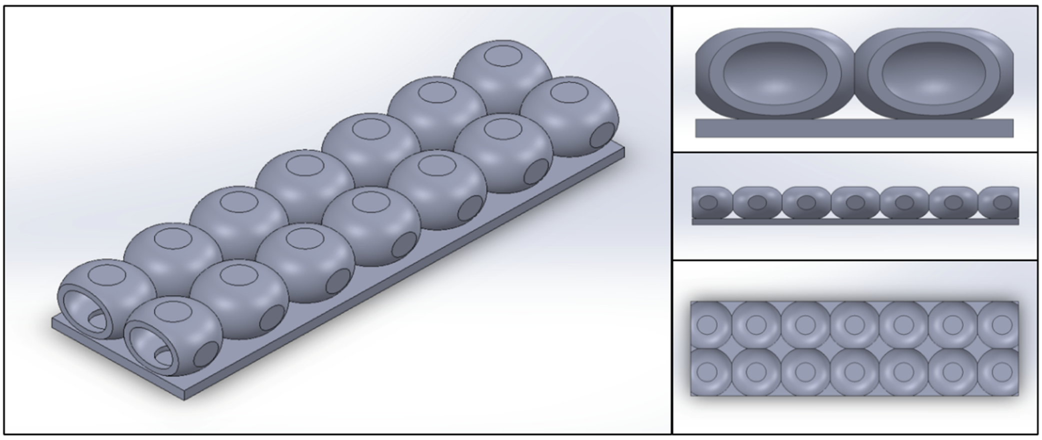

Figure 13. Urchin Design: 3D view (**left**); unit cells (**top right**); side view (**middle right**); and top view (**bottom right**).

2.7. Venus Design

Sponges, representing an ancient lineage of metazoans, have a fossil record dating back over half a billion years [29]. These organisms have maintained their simple body plans throughout their evolutionary history since the mid to late Proterozoic era. Although sponges lack the physiological complexities of higher metazoans, they possess the ability to synthesize a variety of intricate skeletal elements called spicules, composed of either silica or calcium carbonate. Siliceous sponge spicules, in particular, have garnered significant attention due to their precise hierarchical fabrication, species-specific nanoscale structural intricacies, fracture-resistant mechanical properties, and relatively rapid biosynthesis rates. They serve as model systems for analyzing biosilica nanofabrication and translating the underlying mechanisms into the synthesis of new nanostructured materials and devices for advanced applications [30].

However, these spicules represent only one level of the hierarchy in the complex skeletal system of sponges. These organisms have evolved robust skeletal architectures capable of adapting to a wide range of physically demanding environmental conditions. The Venus flower basket sponge (Euplectella aspergillum), belonging to the class Hexactinellida, is an example of such a species. It is predominantly found in deep-sea environments and is particularly abundant around the Antarctic continent at depths ranging from 100 to 1000 m, constituting up to 90% of the benthic biomass [29]. The Venus flower basket sponge possesses a remarkably beautiful and intricate outer skeleton characterized by a cylindrical-lattice-like structure with at least six hierarchical levels spanning from nanometers to centimeters [30]. The basic building blocks are spicules that form a locally quadrate, globally cylindrical skeletal lattice, providing the framework for other skeletal components. The cylindrical body is topped with a terminal sieve plate and anchored to the seafloor by numerous flexible anchor spicules.

The grids of the Venus flower basket sponge (Figure 14) are supported by bundles of spicules arranged in vertical, horizontal, and diagonal struts, as shown in Figure 14c. The structural complexity of the glass skeleton exemplifies nature's ability to enhance inherently poor building materials. The mechanical stability of this design arises from the hierarchical assembly of the glass constituents from the nanoscale to the macroscopic scale. The resulting structure can be considered a role model in mechanical engineering, as the different hierarchical levels in the sponge skeleton employ fundamental construction strategies such as laminated structures, fiber-reinforced composites, and diagonally reinforced square-grid cells [31]. The inclusion of diagonal reinforcements allows the basic square skeleton grid to withstand bending, shear, and torsion loads resulting from ocean currents or contact with surrounding organisms, such as crustaceans [30]. Research conducted by Aizenberg et al. [31] concluded that this unique macrostructure overcomes the brittleness of glass and exhibits excellent mechanical rigidity and stability. Interestingly, the diagonal elements only intersect every second rectangle, but upon closer examination, this arrangement proves to be ingenious. The alternating open and closed cell architecture of the grid shares characteristics with the theoretical design criteria for optimized material usage in similar two-dimensional structures. It follows the optimum design strategies described by Deshpande et al. [32], which state that adding crossbeams to the empty squares does not provide any mechanical advantages. The lattice pattern of the Venus flower basket sponge is yet another example of high structural stability achieved with minimal material usage, a common theme in biological systems where critical resources are often limited.

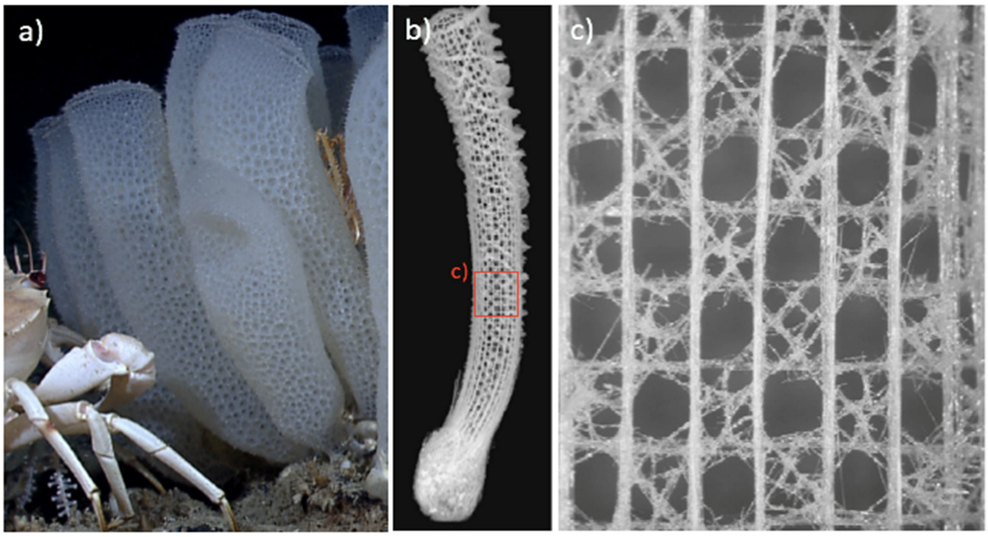

Figure 14. Venus flower basket (Euplectella aspergillum) and its skeleton: (**a**) Within the natural environment; (**b**) Photo of the underlying siliceous cylindrical skeletal lattice by removal of the organic material; (**c**) Close-up of the square grid architecture and regular ordering of the vertical, horizontal and diagonally components of the skeletal system [30].

The core design depicted in Figure 15 was inspired by the skeletal architecture of the Venus flower basket sponge. The rectangular basic pattern was sized to completely enclose the core, while the diagonal pattern comprises pairs of parallel struts intersecting in a series of alternating open and closed cells. In the design of the diagonal struts, two thinner struts were used instead of one thicker strut. Finite element simulations have shown that this arrangement, with separate components and displacements from the nodes of the square lattice, reduces strain accumulation at the nodes and achieves a more diffuse strain field overall [30]. The volume of this core design is 7137 mm^3, falling within the specified tolerance.

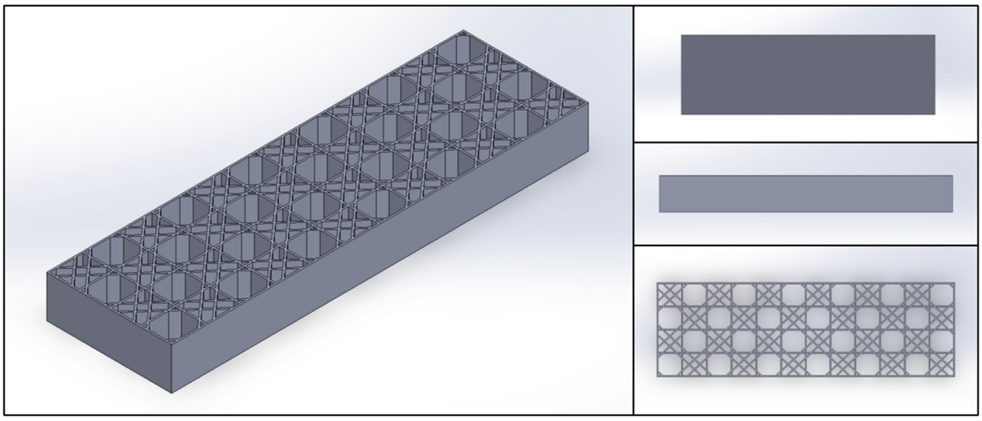

Figure 15. Venus Design: 3D view (**left**); unit cells (**top right**); side view (**middle right**); and top view (**bottom right**).

3. Finite Element Simulations

The simulation procedure for predicting the flexural behavior of the sandwich structures with a three-point bending test using ANSYS Workbench is described in this section. The physical test and simulation are based on Figure 16, where a stationary specimen is bent in the middle between two supports with a cylindrical punch. The purpose of the three-point bending test is to apply tensile and compression loads to the surface layers and shear and compression loads to the core structures, allowing for the investigation of bending stiffness and core shear resilience [33].

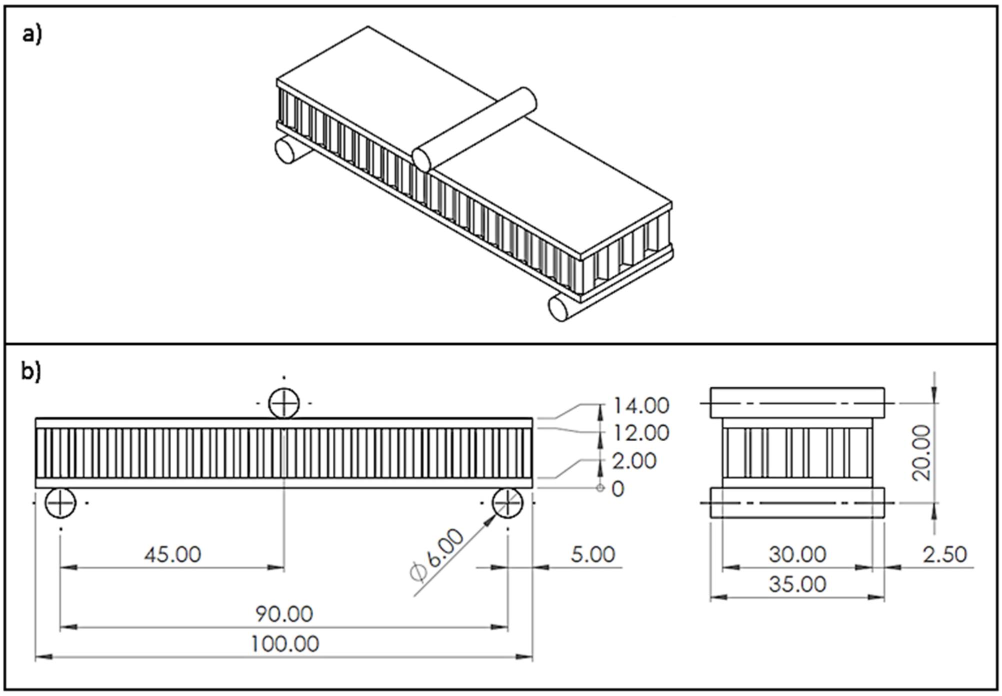

Figure 16. (**a**) Isometric view of the setup used in the simulation; (**b**) Dimensioned layout of the simulation with two different views (all dimensions are in mm).

To perform the simulation, the biomimetic designs created in SolidWorks were saved as STEP files and imported into ANSYS Workbench. Due to the small dimensions and need for accuracy, a simulation with volume elements was chosen. This type of simulation considers shear forces in the thickness direction, providing higher accuracy compared to other approaches such as Layered Shell or Shell-Solid-Shell.

In the three-point bending test, the behavior of the three cylinders involved in the setup needs to be defined. The two lower cylinders are fixed during the simulation to prevent any displacement, replicating the behavior of the sub-tool in the physical experiment. The sandwich structure being tested is free to move in any direction, and its deformation behavior is controlled by the fixed and moving cylinders. The analysis settings were adjusted to use twenty time steps, allowing for precise load curve calculations at intervals of half a millimeter of displacement. The "Large Deflection" module was activated to account for stiffness changes resulting from deformations. During the simulations, the punch is lowered by 10 mm.

Five contact conditions were determined for the simulations. The surfaces of the three tool cylinders were set to interact with the respective surfaces of the cover sheets, and the surfaces between the core and cover layer were also considered. The core and face sheets were assigned the "Bonded" contact condition to ensure a strong bond between them, stronger than the core material itself. The upper tool and upper surface layer were also set as "Bonded" since no relative movement was expected between these surfaces. For the surfaces of the two solid cylinders with the lower surface layer, the "Frictional" contact condition was chosen with a friction coefficient of 0.3, corresponding to the nylon-steel contact pair.

An adaptive meshing technique was employed using SOLID 187 elements in ANSYS. This technique automatically reduces the size of individual elements in multiple calculation runs to obtain ideal elements. The mesh pattern consists of various element sizes, with the smallest elements concentrated in high-stress areas. The convergence value, set at 7%, indicates the maximum deviation of the result value, and ANSYS repeats the calculation process until the convergence value is maintained or the maximum number of repeat loops is reached. The mesh was refined at the tool contact surfaces and in the middle of the core structure, focusing on the most heavily stressed areas.

The face sheets of the sandwich panels were made of carbon-fiber-reinforced nylon, while the core was made of polylactic acid (PLA). Material properties were obtained via tension and compression tests on 3D printed samples using eSun ePA–CF (Nylon + Carbon Fiber) and eSun PLA+ filaments with 1.75 mm diameters. The material properties are provided in Table 1. The cylinders used in the simulation were made of steel, with Young's modulus of 200 GPa, Poisson's ratio of 0.3, and yield strength of 250 MPa.

Table 1. Material properties of the 3D printed carbon-fiber-reinforced nylon (ePA-CF) and polylactic acid (PLA+).

Density [kg/m^3]	Young's Modulus [MPa]	Poisson's Ratio [−]	Bulk Modulus [MPa]	Shear Modulus [MPa]	Tensile Yield Strength [MPa]	Tensile Ultimate Strength [MPa]
1240	781	0.35	868.33	289.44	42	62
1240	1405	0.38	1951.4	509.06	40	40

Figure 17 illustrates a deformed sample sandwich panel under the three-point bending simulation, showing the behavior and response of the structure under the applied loads. Table 2 presents the result values obtained from the simulations, comparing different biomimetic designs presented in Section 2.

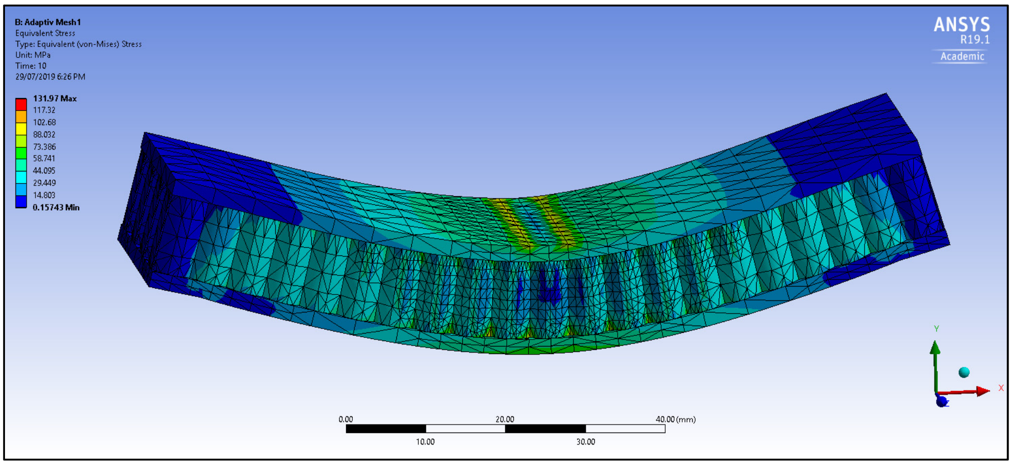

Figure 17. Sandwich panel after 3-point bending simulation, with the minimum equivalent (von Mises) stress of 157.43 kPa and the maximum equivalent (von Mises) stress of 131.97 MPa.

Table 2. Simulation results for different biomimetic designs.

Design	Dispalcement	Force Reaction	Stress	Point of Failure	Stiffness
	[mm]	[N]	[MPa]	[mm]	[N/mm]
Honeycomb	10,047	2126.8	103.08	4.03	214
Diatom 1	10,042	1589.3	184.87	3.00	163
Diatom 2	10,038	1922.2	148.1	3.34	196
Double-helix	10,030	1243.5	115.14	4.33	125
Double-sine corrugated	10,048	1401.0	167.88	4.42	145
Leaf	10,058	2135.1	134.33	3.80	216
Triangular	10,099	2143.7	119.46	3.59	215
Urchin	10,095	1624.4	112.31	4.56	165
Venus	10,054	2174.1	110.52	3.50	220

Figure 18 presents a summary of all nine force-displacement curves generated from the simulations. It illustrates the significant variations in stiffness among the different designs. While the deviations in stiffness for the strongest designs are relatively small, the difference between the minimum and maximum stiffness is approximately 45%. The objective of the simulations was to gain insight into the flexural behavior of each design and subsequently validate the strongest designs using physical experiments.

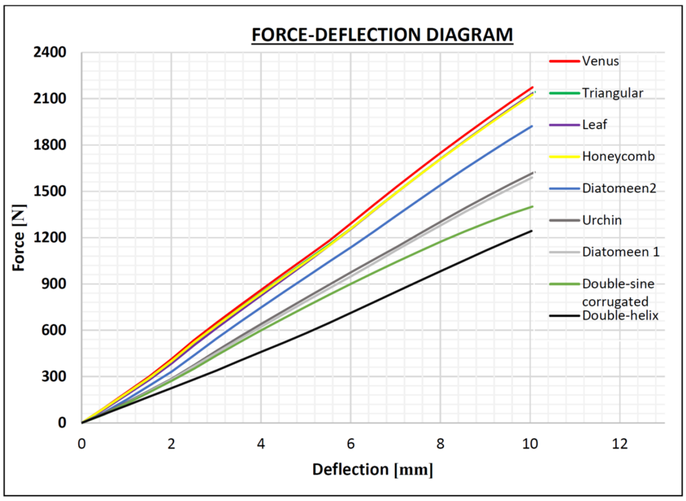

Figure 18. Combination of the simulated Force-Displacement curves of all designs.

In comparison to the widely used Honeycomb design, known for its high mechanical load capacity in various industrial applications, four other designs exhibit comparable strength. This fact is clearly depicted in the bar chart shown in Figure 19. Consequently, the following five designs were selected for manufacturing and subsequent physical testing: Honeycomb design, Diatom 2 design, Leaf design, Triangular design, and Venus design.

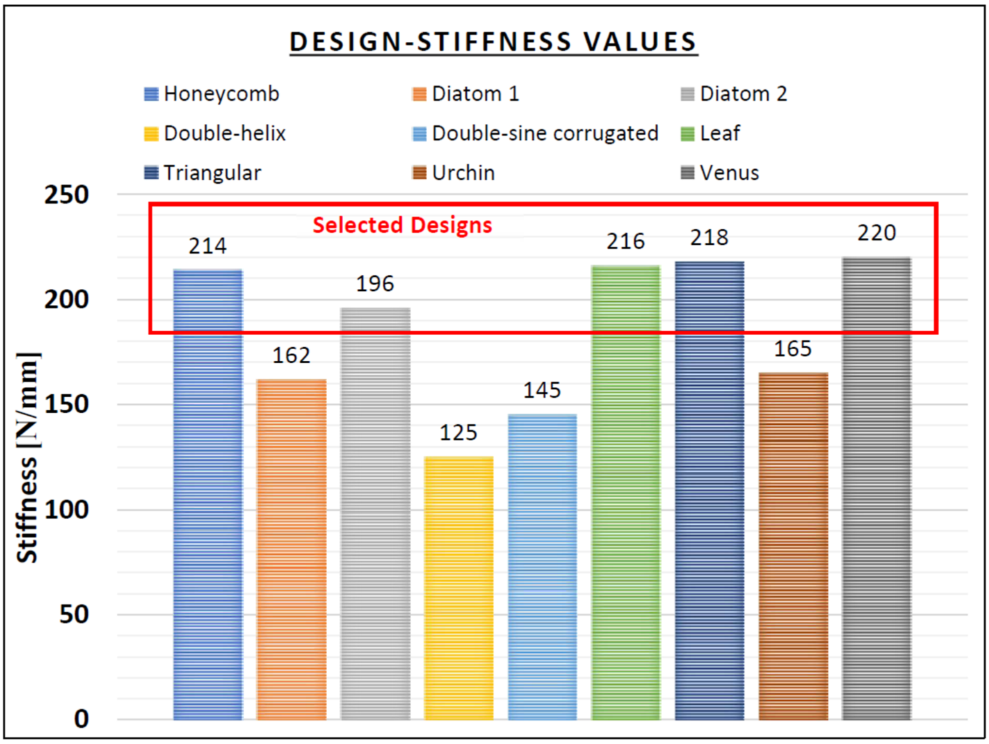

Figure 19. Bar chart representing the stiffness values for each design, with the best results highlighted inside the red box.

4. Three-Point Bending Tests

The fused deposition modeling (FDM) technique was employed for the 3D printing of the test samples in this study. The printing parameters used for the FDM process are detailed in Table 3. In the 3D printing setup, a printer equipped with FDM technology was utilized. This printer consists of a heated nozzle that melts the plastic filament and deposits it onto a build platform. The layer-by-layer deposition allows for precise control over the shape and structure of the printed object. A visual representation of the 3D printing setup is provided in Figure 20, illustrating the printer, filament box, and build platform.

Table 3. Parameters of the printing process for the two materials used for printing the face sheets and the cores.

	PLA+	CF Nylon
Nozzle diameter [mm]	0.4	0.4
Layer thickness [mm]	0.2	0.2
Infill density [%]	100	100
Print temperature [°C]	200	250
Build bed temperature [°C]	60	40
Print speed [mm/min]	1800	1800
Flow rate [−]	0.9	1
Infill pattern [deg]	-	+45/−45
Build bed adhesion	-	Double-side tape
Nozzle material	Brass	Titanium

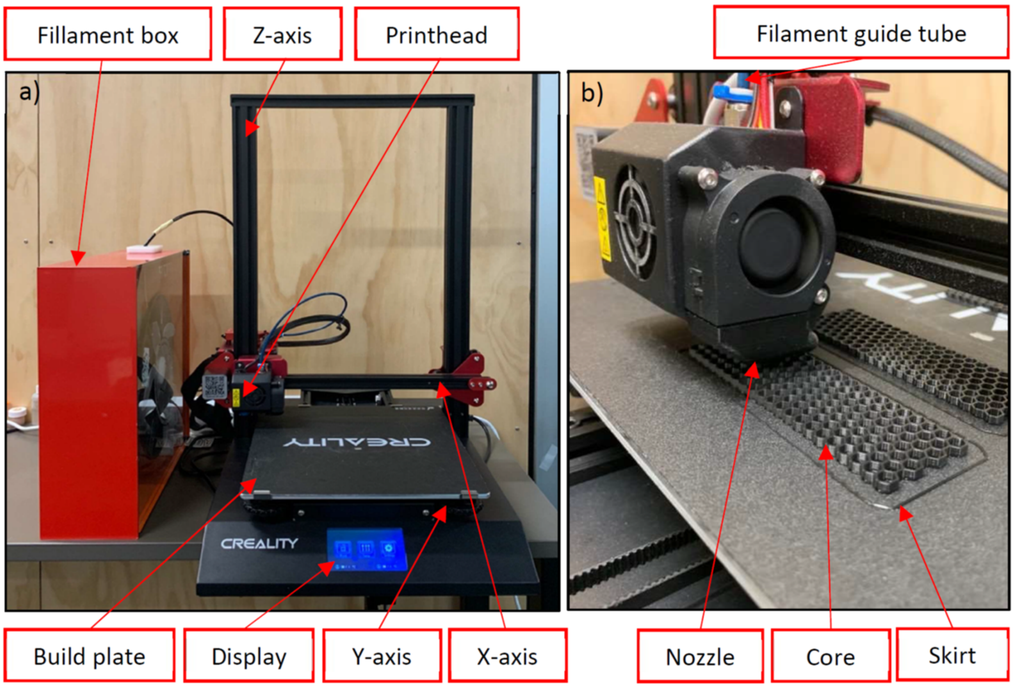

Figure 20. (**a**) The used 3D printer for the production of the sandwich cores; (**b**) Close-up of the printing process.

To construct the sandwich structure, the face sheets and cores were printed separately. Once the printing of the face sheets and cores was completed, they were joined together to form the sandwich structure. To achieve a strong and durable bond between the layers, a two-part epoxy paste adhesive (Selleys Araldite Super Strength) was applied.

The three-point bending experiment was conducted after the manufacturing process, employing a testing speed of 5 mm/min. The three-point bending test applied tensile or compressive loads to the top layers and shear and compression loads to the core structures. This test was chosen specifically to examine the effective bending stiffness of the overall structure as well as the core shear stiffness of the developed designs. Various failure possibilities were anticipated in the three-point bending test:

1. Face sheet failure due to inadequate material properties or insufficient thickness.
2. Flexural crushing of the core caused by insufficient flatwise compressive strength or excessive beam deflection.
3. Local crushing of the core caused by low compression strength.
4. Face sheet wrinkling and delamination caused by insufficient strength of the adhesive.

The objective of the study was to investigate the load behavior of the developed core designs while ensuring the occurrence of core failure and minimizing other failure possibilities. To prevent failure of the cover layers, stronger and more flexible materials were used compared to the core structures. Moreover, the risk of delamination was mitigated by employing a high-strength two-component epoxy resin paste adhesive. These precautions were implemented to primarily observe failure modes 2 or 3.

Upon completion of the samples, the three-point bending experiment was carried out under identical conditions. The upper tool was displaced in the negative Y-direction until the failure of the samples occurred. The failure was evident from the decreasing punch force recorded by the testing machine in the force-displacement diagram. The precautions taken to ensure core failure proved successful in the experiments, as no face sheet failures were observed. Delamination, although occasionally detected after substantial deformation of the sandwich structures, always occurred subsequent to core failure.

During the experiments, a decline in the measured force profile was observed before any visible external damage occurred. It can be speculated that initial damage, such as cracks or deformations of the PLA+ material, took place within the core structures. Subsequently, visible external damage, including cracks in the outer walls or deformations, became evident upon further loading. After the experiments, the surface layers and adhesive residues were removed to investigate the failure cases.

Notably, the type of failure observed depended on the core design. Crack formation from the underside towards the top edge was observed in the Honeycomb designs, Triangular designs, and Venus designs, as depicted in Figure 21. This cracking indicated shear failure, attributed to the generation of tensile forces in the direction of the long edge of the structure. The crack paths in these designs indicated that the Venus design, featuring diagonal walls for reinforcement, hindered direct crack propagation via the structure and exhibited the longest crack path.

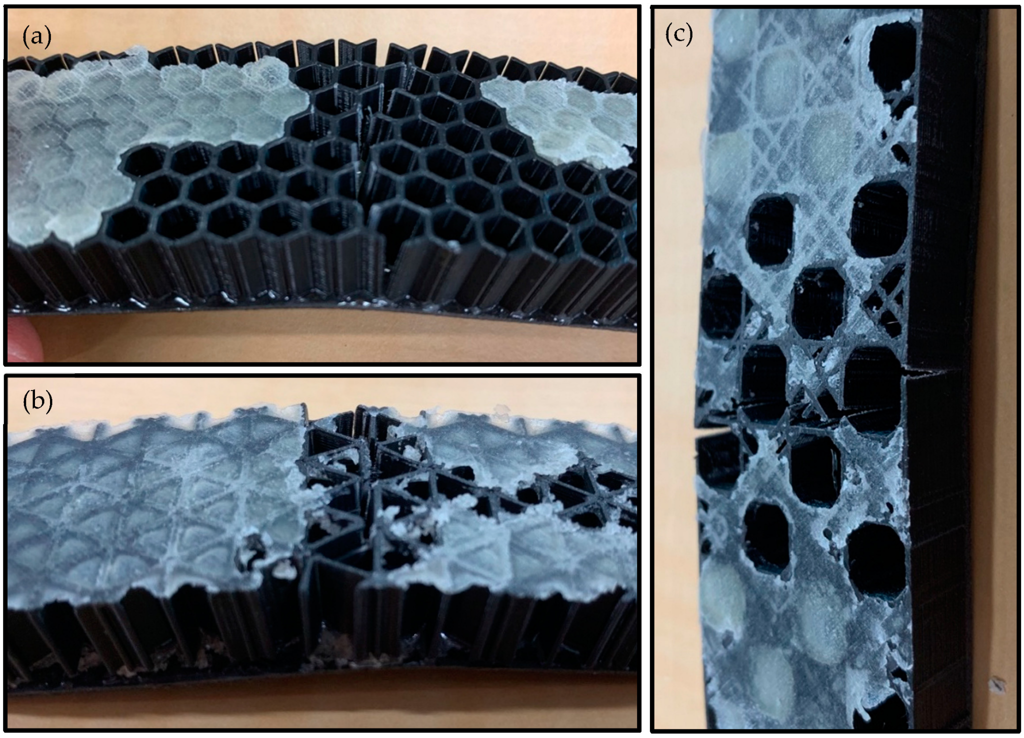

Figure 21. Crack formation as failure cause of the (**a**) Honeycomb design, (**b**) Triangular design, and (**c**) Venus design.

Conversely, the sandwich composites with the Leaf design and Diatom 2 design did not exhibit cracks but instead showed deformations near the stamp at the outer edges. Figure 22 illustrates the core structures of both designs after the test, highlighting the deformation failures resulting from compression. Outward bending of the outer walls was observed, and in the case of the Leaf design, detachment of the material connection occurred. The deformations indicated that the walls in these designs were not sufficiently rigid. Comparing all designs, it was observed that the walls of the individual cells in the structures shown in Figure 22 were longer. A compressed form of these structures could potentially prevent deformation failure.

Three tests were conducted for each set, and the average values were reported. Significant differences in stiffness values can be observed among the designs. Figure 23 presents a bar chart summarizing the average stiffness values for all designs. The Leaf design, Triangular design, and Venus design demonstrate superior performance compared to the Honeycomb design. While the Leaf design shows a similar range with a deviation of 13.5%, both the Triangular design and Venus design exhibit significantly higher stiffness values. The Triangular design demonstrates a 36.7% difference compared to the Honeycomb design, and the Venus design showcases a 37.8% improvement, achieving the highest average value at 416 N/mm. The Diatom 2 design has reduced its distance from the Honeycomb design by 1.5% to 6.9% compared to the simulation.

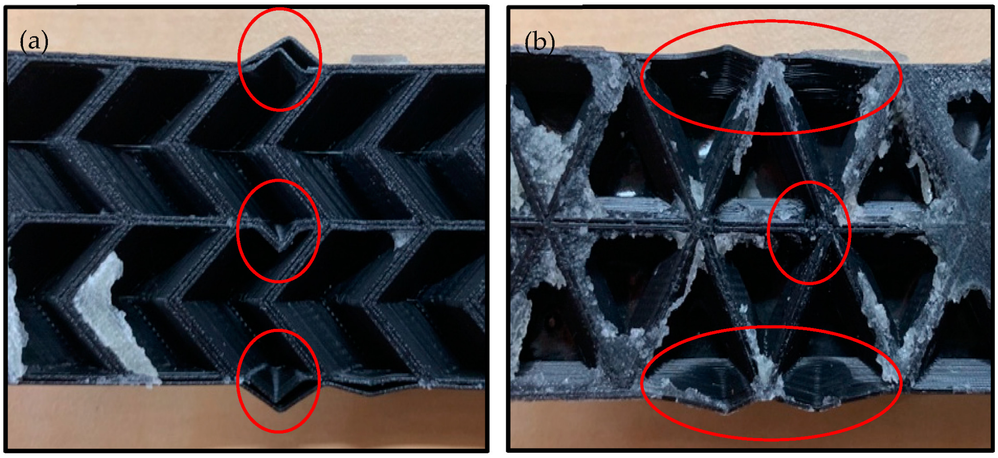

Figure 22. Deformation as failure cause of the: (**a**) Leaf Design, (**b**) Diatom 2 Design.

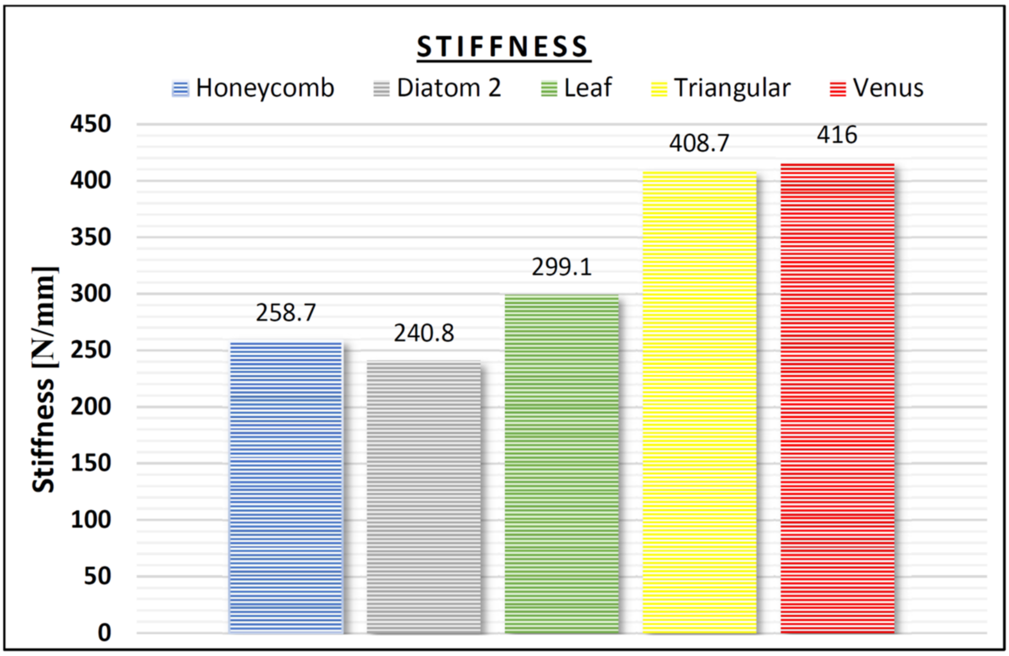

Figure 23. Average stiffness values of the tested designs.

The experiments confirm the advantage of the Leaf design, Triangular design, and Venus design for highly rigid composite structures. Particularly, the latter two designs exhibit significantly improved stiffness values, making them potential alternatives to the widely used honeycomb design. The Leaf design and Diatom 2 design demonstrate similar stiffness values to the Honeycomb design, necessitating the consideration of other advantageous properties for selecting the appropriate design for specific applications.

The maximum yieldable force is another crucial parameter for many applications, requiring a comparative analysis of the designs. Figure 24 presents the average values of all designs in a bar chart, clearly demonstrating the differences in this property. The Honeycomb design occupies the middle ground with a value of 1129.9 N. The Leaf design tolerates noticeably less force with a deviation of 14.7%, while the Diatom 2 design exhibits the lowest tolerance with a deviation of 43%. The Triangular design and Diatom design also show superior performance in this regard. Among the tested designs, the Venus Design achieves a significantly better result with a 14% increase. The sandwich composites featuring the Triangular design prove to be even more robust, with a deviation from the honeycomb design of 18.3% and an average value of 1283.5 N.

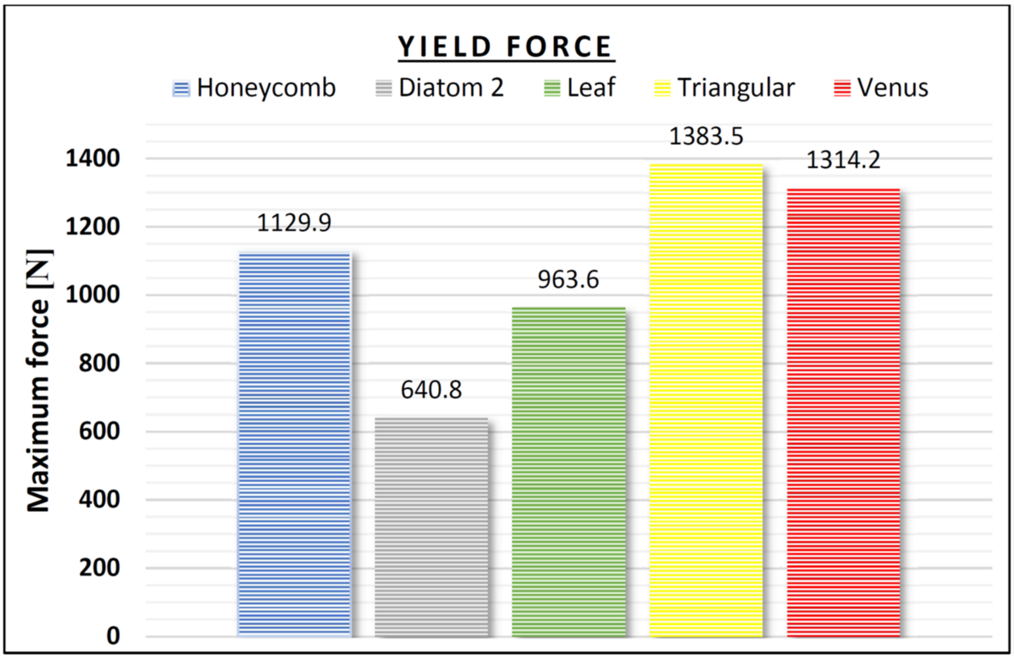

Figure 24. Average force values at the peak of the measured force-displacement curves of the tested designs.

The wide application of the Honeycomb design in various industries has been emphasized before. Its advantage lies in its high resistance to mechanical loads combined with a remarkably low weight. However, this work identifies two structures, the Triangular design and the Venus design, capable of withstanding considerably higher loads under similar conditions. These designs could serve as better alternatives to the Honeycomb design for specific applications.

The flexibility of a design provides insights into its maximum potential deformability at the point of maximum resistance. This property can be of great importance under certain circumstances, where specific deformations may be inevitable or occur due to unexpected external factors. Consequently, the tested designs were also compared based on this criterion. Figure 25 illustrates the punch displacement at maximum resistance in a bar graph. It is evident that the Honeycomb design outperforms all the tested designs, resulting in deviations ranging from 56.6% to 37.3%.

If flexibility is a critical factor within an application, the tested designs, at least in their current form, may not be considered suitable alternatives. However, structural modifications could potentially improve this property. Additionally, other core structures designed in this work exhibit promising flexibility characteristics. Simulation results of the three-point bending test for sandwich composites with the double-helix design, double-sine corrugated design, and urchin design demonstrate particularly high flexibility properties, surpassing even the failure time of the Honeycomb design.

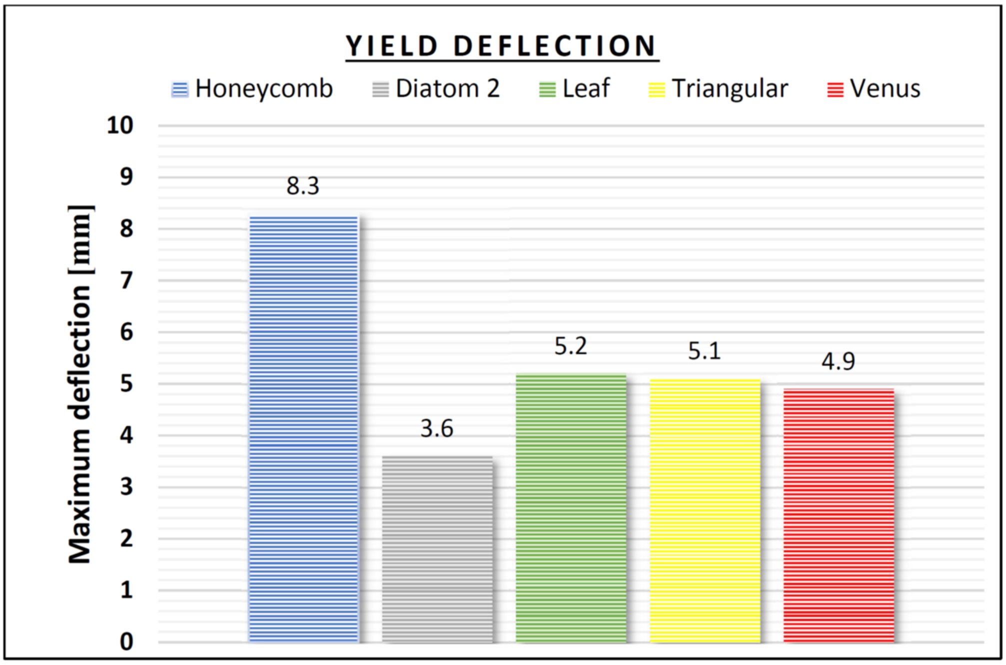

Figure 25. Average deflection values at the point corresponding to the maximum force of the tested designs.

5. Conclusions

This paper focused on the development, modeling, simulation, and testing of lightweight sandwich panels with a particular emphasis on core structures inspired by biological models. The study aimed to explore the mechanical properties of these innovative core designs and compare them to the widely used Honeycomb core. Using an extensive research process, eight biomimetics core structures were developed and analyzed, with their stiffness, bearable load, and flexibility evaluated in the context of sandwich composites.

The results revealed the great potential of the developed core designs, particularly the Triangular design and the Venus design, which exhibited an impressive increase in stiffness by up to 38% and a higher load-bearing capacity by 18% compared to the Honeycomb core. These findings highlight the efficacy of integrating bionic principles into lightweight sandwich structures, offering improved mechanical properties and showcasing the advantages of using biomimicry as an approach in engineering.

While this research has provided valuable insights into the mechanical performance of the developed core structures, there are several avenues for future exploration. Further investigations could explore other important properties for industrial applications, such as crash behavior, aeration, manufacturability, insulation, and damping potential. It would also be worthwhile to explore variations in geometries, dimensions, manufacturing processes, and materials to assess their impact on the mechanical properties of the sandwich panels. Comparisons with other existing core geometries, such as the Fold Core, would provide additional context and aid in further classification of capabilities.

This study underscores the potential of biomimetics as a source of inspiration for innovative solutions in engineering lightweight sandwich structures. By mimicking nature's designs, significant improvements in mechanical properties can be achieved, leading to more efficient and sustainable products. Continued research and development in this field will pave the way for further advancements and novel applications of bionic-inspired sandwich composites.

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