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Review

Optimization of Composite Sandwich Structures: A Review

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Abstract

Composite sandwich structures play a significant role in various engineering applications due to their excellent strength-to-weight ratio, durability, fatigue life, acoustic performance, damping characteristics, stealth performance, and energy absorption capabilities. The optimization of these structures results in enhancing their mechanical performance, weight reduction, cost-effectiveness, and sustainability. This review provides a comprehensive analysis of recent advancements in the optimization techniques applied in the case of composite sandwich structures, focusing on structural configuration, facesheets, and innovative cores design, loading conditions, analysis methodologies, and practical applications. Various optimization procedures, single- and multi-objective algorithms, Genetic Algorithms (GAs), Particle Swarm Optimization (PSO), and Machine Learning (ML)-based optimization frameworks, as well as Finite Element (FE)-based numerical simulations, are discussed in detail. It highlights the role of core material and geometry, face sheet material selection, and manufacturing limitations in achieving optimal performance under static, dynamic, thermal, and impact loads under various boundary conditions. Furthermore, challenges such as computational efficiency, experimental validation, and trade-offs between structural weight and performance are examined. The findings of this review offer insights into the recent and future research directions of optimizing sandwich constructions, emphasizing the integration of advanced numerical techniques for analysis and efficient structural optimization.

Keywords: composites; sandwich structure; optimization; sustainability; machine learning; genetic algorithm

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1. Introduction

Sandwich composites stand at the forefront of material science, offering an exceptional combination of lightweight properties, high strength, and structural performance [1–5]. A typical sandwich panel is shown in Figure 1, where the upper and lower facesheets are made from high-performance materials and are bonded to a lightweight inner core. The most commonly used materials in the facesheets are carbon fiber, glass fiber, and Kevlar, while metals include Aluminum (Al) and steel. Lightweight cores can be honeycomb (Al, Nomex), foam (polymer, Al), or other structures. The facesheets mainly contribute to the structure's bending strength and stiffness, and the core facilitates the transfer of shear forces between the top and bottom facesheets, while bonding materials like epoxies are used to transfer loads between the facesheets and core.

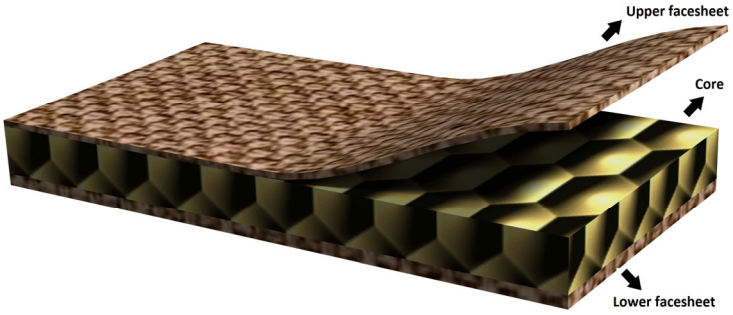


Figure 1. A typical sandwich panel.

Innovative sandwich structures have an outstanding stiffness-to-weight ratio, making them indispensable for industries where reducing weight while maintaining structural integrity is critical. These types of sandwich constructions are extensively utilized in the aerospace [6–8], automotive [9–11], marine application [12–14], and renewable energy sectors [15–17], where their ability to enhance performance, durability, and efficiency is required. Beyond their mechanical advantages, the sandwich constructions provide additional benefits such as energy absorption [18–20], vibration damping [21–24], thermal insulation [25], and acoustic properties [26,27]. Their versatility and adaptability have made them the basis for modern engineering applications like aircraft structures, high-speed trains, automobiles, wind turbine blades, and even sports equipment. As a result, sandwich composites continue to drive progress in material science, leading to further lighter, stronger, and durable structures across a wide range of applications.

Creating highly efficient sandwich structures is becoming more complex with the advancement of modern analysis techniques, which are focused on modelling structures simultaneously at the micro and macro levels. These procedures require simultaneous control over both material tailoring and overall structural performance.

Breakthroughs in manufacturing, such as 3D printing, are leading to innovations in modern sandwich structures, mainly the development of more efficient cores. These developments provide the possibility for complex core designs like lattice and bio-mimic structures.

The growing complexity of modern sandwich structures has created challenges for design engineers, emphasizing the critical need to adopt advanced analytical tools, particularly computational optimization, to achieve the full potential of these recent advancements. The selection of adequate optimization algorithms [28] depends on the specific characteristics of the optimization problem, such as the objective function, design variables, and design constraints, which play a key role in defining the most effective structure. In the case of composite materials, especially sandwich constructions, the design space is exceptionally broad, including a wide range of material variables (e.g., material types of facesheets and cores, a layup sequence in the facesheets) and geometric parameters. Consequently, as design problems become increasingly complex, the development and implementation of efficient optimization methodologies are essential to managing these complexities and achieving optimal solutions.

This review article is organized as follows: Section 2 offers a concise introduction to the formulation and classification of optimization problems. Section 3 details the systematic review methodology, and Section 4 describes the authors' motivation for writing this review article. Section 5 explains the recent developments in analytical techniques to be utilized for modern optimization algorithms. Furthermore, Section 6 examines optimization studies focused on innovative core design. Section 7 provides an overview of recent optimization algorithms utilized for designing sandwich constructions under various loading conditions. Section 8 details an application-based review of optimization studies

on sandwich constructions. Section 9 explores the use of Genetic Algorithms for the optimization of sandwich structures. Finally, Section 10 summarizes the main conclusions of the literature review in the field of composite sandwich structures' optimization.

2. Optimization Problem Formulation and Optimization of Algorithms

An optimization problem consists of three fundamental elements, i.e., single- or multi-objective functions, design variables (continuous or discrete), and design constraints (equality or inequality). The general formulation of a single-criterion nonlinear programming problem is represented by the following expressions [29]:

$$\text{optimize } f(x) \;\; x = \{x_1, x_2, x_3, \ldots, \; x_n\} \tag{1}$$

subject to:

$$g_i(x) \leq 0 \qquad i = 1, 2, \ldots, m$$

$$h_j(x) = 0 \qquad j = 1, 2, \ldots, \; p$$

where: $f(x)$ is a multivariable nonlinear function, $g_i(x)$ and $h_j(x)$ are nonlinear inequality and equality constraints, respectively.

An illustration of the most commonly used objective functions, design variables, and design constraints for a composite sandwich structure is shown in Table 1. Depending on the complexity of the optimization problem, various optimization algorithms are available to obtain either the global or local optima. For complex optimization problems, obtaining the exact solution is somehow difficult, so it is known as the quasi-optimal solution. In case of a multi-objective optimization problem, all the feasible solutions are present as a Pareto front for two or more conflicting objective functions. Categorization of the algorithms used for solving the optimization problem is shown in Table 2.

Table 1. Most commonly used objective functions, design variables, and design constraints for sandwich constructions.

Objective Functions	Design Constraints	Design Variables
Min. weight Min. cost Max. specific energy absorption Min. transmitted load Max. sound transmission loss, etc.	Total deflection (e.g., tip deflection, twist angle, etc.) Total buckling load Facesheet buckling load Core shear buckling load Facesheet stress Stiffener stress Stiffener web buckling load Eigenfrequency Bending stiffness Torsional stiffness, etc.	Facesheet thickness Number of plies in the facesheet Thickness of plies Fiber orientation in the layers (unidirectional or bidirectional ply) Stacking sequence in the laminate Fiber material (Carbon/Glass/Kevlar fiber) Core thickness Core material (Nomex honeycomb, Al/Polyurethane foam), etc.

Figure 2 presents a systematic optimization framework for composite sandwich structures. The process begins with problem formulation, where key components are defined: (1) objective functions (e.g., minimizing weight and cost while maximizing stiffness), (2) design constraints (e.g., stress limits, manufacturability requirements), and (3) design variables (e.g., core topology, facesheet thickness, material selection) (see Table 1). Depending on problem complexity, suitable optimization algorithms—such as Genetic Algorithms, Particle Swarm Optimization, or gradient-based methods—are selected (see Table 2) and coupled with either analytical models or Finite Element simulations for structural analysis. The simulation outputs are used for evaluating the objective functions. Furthermore, to

evaluate the performance of optimization algorithms, comprehensive statistical analyses are conducted. The final stage involves experimental testing or high-fidelity numerical simulation studies to validate the optimized design, to conform to the structural requirements under operational loading conditions.

Table 2. Classification of optimization algorithms [30].

Classification	Explanation/Examples
Combinatorial methods	Each variable takes one of a finite set of values, e.g., linear programming.
Deterministic optimization	The problem is well defined in analytical form and a unique solution is possible, e.g., hill climbing.
Stochastic algorithms	Quasi-optimal solutions are possible based on a random search, e.g., mathematical programming, ant colony optimization, immune system methods, memetic algorithms, scatter search and path relinking, particle swarm, GAs, differential algorithms.
Mixed algorithms	Combine the best features of deterministic and stochastic algorithms. Work as a black box, e.g., chaotic neural networks.

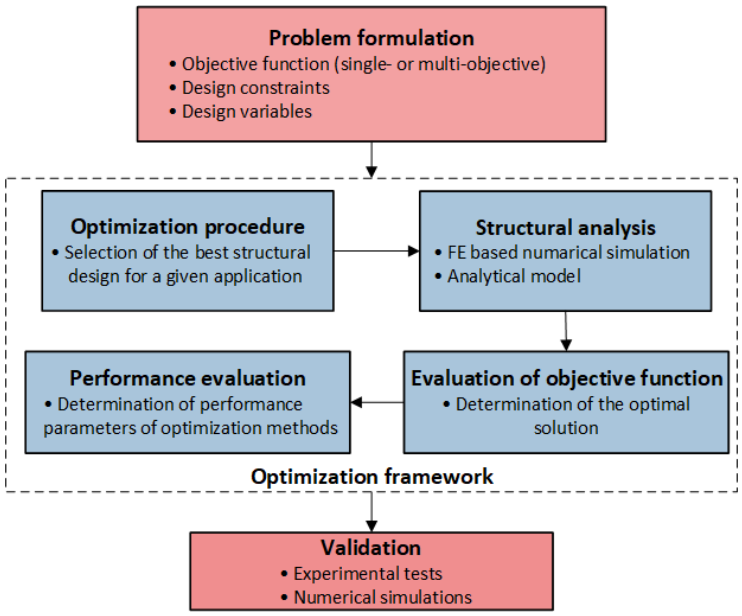


Figure 2. A typical scheme for optimization of composite sandwich structures.

3. Methodology Adopted to Conduct This Review Study

The Scopus database serves as the primary source for identifying research articles relevant to the proposed topic. Initially, a search query was applied using the following parameters: TITLE-ABS-KEY((("optimization" OR "machine learning") AND ("composites" OR "structures") AND ("sandwich"))) AND PUBYEAR > 2015 AND PUBYEAR < 2025 AND (LIMIT-TO(PUBSTAGE, "final")) AND (LIMIT-TO(LANGUAGE, "English")). This search resulted in 1,703 research articles, including both journal and conference papers. In the next step, the entire dataset was imported into the Zotero tool for systematic organization/categorization and further citing in this review article. Additional data was supplemented from other sources such as Web of Science, ScienceDirect, MDPI, and Google Scholar, focusing on articles related to the research topic. A thorough study of the titles, abstracts, and conclusions, as well as a detailed study of the articles, was conducted in

some cases. The publications are categorized into the following key areas: review articles, applications (aerospace, automotive, marine), core design, impact/blast loading, dynamics/vibration, acoustics performance, ML-based studies, damage tolerance/fracture mechanics, Structural Health Monitoring (SHM), process parameters, and topological optimization studies.

The statistical analysis reveals that most of the publications originated from China, contributing 744 articles, followed by the United States with 151 articles, as illustrated in Figure 3. Additionally, Figure 4 highlights a noticeable upward trend in the number of publications starting from 2015, rising to 329 articles by 2024. The growing interest among researchers in this topic underscores its significance and provides strong motivation for the authors to prepare a comprehensive review of contemporary optimization studies related to sandwich structures.

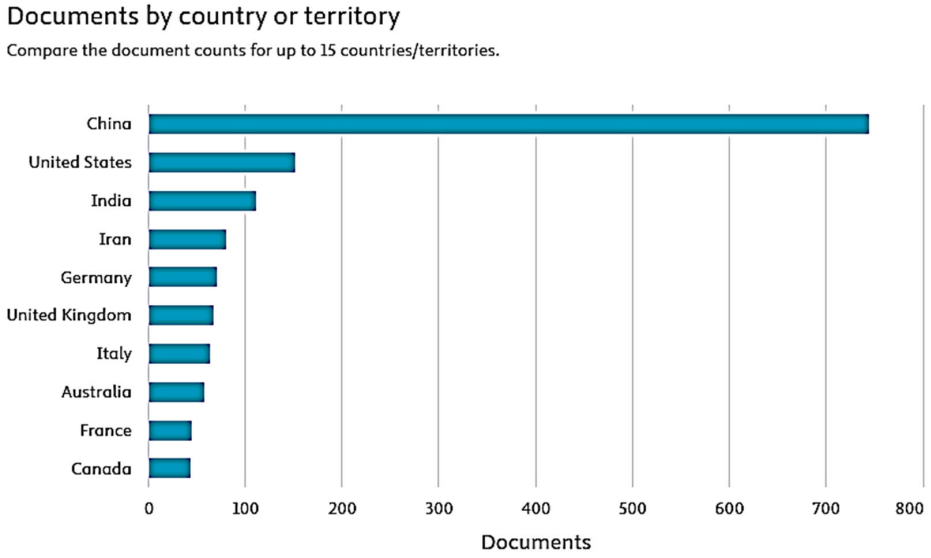


Figure 3. Document count as per the country/territory [31].

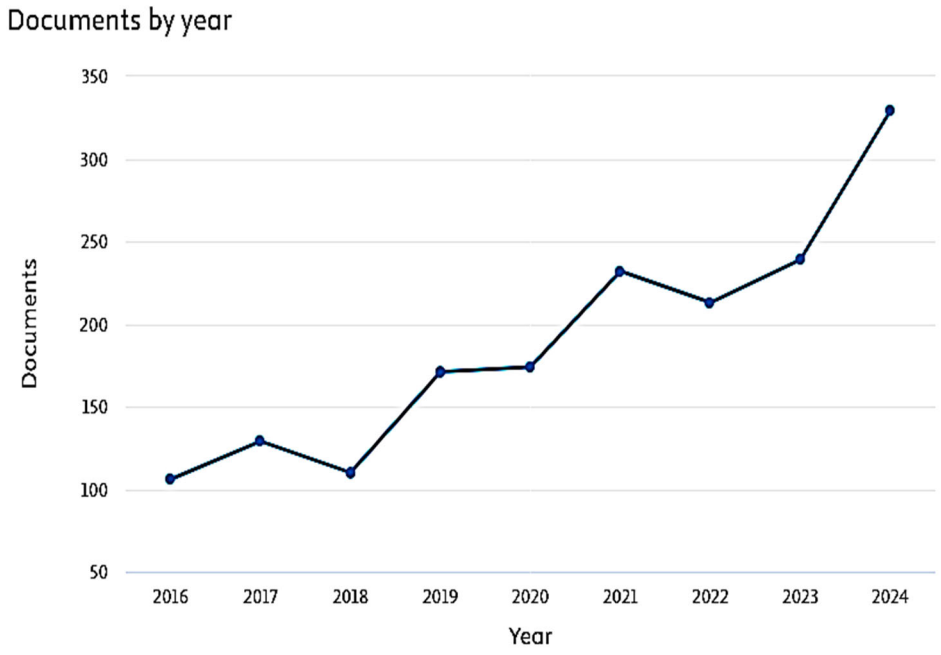


Figure 4. Document count per year [31].

4. Motivation to Prepare This Review Article on the Optimization of Composite Sandwich Constructions

Composite structures are used in various applications due to their effective performance characteristics. Recently, many review articles have been published focusing on the design of composite structures. Although numerous reviews cover various advanced topics, a gap remains that requires a thorough study on the optimization of sandwich constructions. Below is a detailed summary of relevant review articles.

A review study was carried out by Li and Yang [32] to outline the progress in theoretical models, simulations, and experimental methods for honeycomb structural designs. The study discussed the simulation models and their associated challenges, such as high computational costs, material heterogeneity, and lack of generality. The study suggested future directions by incorporating ML tools, comprehensive datasets, and hybrid (simulation–experimental) models to address the complexity of problems. Garg et al. [33] highlighted the analysis of Functionally Graded Material (FGM) structures under different loading conditions with an emphasis on newly developed analytical techniques. The study emphasized the use of Higher Order Shear Deformation Theory (HOSDT), Zigzag Effects, along with transverse normal stresses for accurately predicting the structural responses. Sandeep and Srinivasa [34] reviewed the advancements in free vibration analysis of different structural elements (laminated composites and sandwich structures), highlighting the development of refined theories, analytical models, numerical techniques, and experimental methods. The study emphasized the need for further research on nonlinear analysis, natural fiber usage, and accurate dynamic behavior prediction. Birman and Kardomateas [35] explored contemporary advancements in sandwich structures, emphasizing sophisticated analytical models, innovative designs like functionally-graded cores and smart materials, multifunctional features, environmental impacts, and diverse applications in aerospace and civil engineering. Sayyad and Ghugal [36] critically reviewed the literature on bending, buckling, and vibration analysis of laminated composite and sandwich beams, highlighting the need for refined theories incorporating geometrical and material nonlinearities. The article proposed the future research directions, and the applications of advanced analytical and numerical methods used in civil, marine, and aerospace structures.

Additive manufacturing [37] is a revolutionary technology in modern fabrication, offering cost-effective, rapid, and precise production of complex composite structures. Several reviews discussed the composite structures with innovative core designs, including studies on cellular cores [38], biomimetic structures [35,36], 3D-Printed Fiber-Reinforced Polymers (FRP) [39], bio-inspired cores [40], novel core designs [41], customized design cores [42], and lattice cores [43]. Researchers have extensively reviewed innovative core designs and advancements in lattice structures. Furthermore, these studies are focused on optimizing functionally graded materials, exploring smart materials, and improving manufacturing techniques. These developments aim to improve the sandwich constructions' mechanical properties and interfacial strength of facesheets, as well as the core for use in aerospace, automotive, and biomedical applications.

Sandwich structures with lightweight cellular cores are widely used in aerospace applications for their excellent energy absorption and impact resistance characteristics. Honeycomb structures, in particular, show excellent energy absorption under dynamic loading, influenced by cell geometry and facesheet properties. Most of the review studies highlighted complex failure modes for sandwich structures under impact loading with emphasis on lattice cores [43], metal-based cores [44], structural analysis [45], aerospace applications [46], and low velocity impact analysis [47]. These review studies emphasize the necessity of ML techniques such as Neural Networks (NNs) for damage assessment under impact loading [48].

Recent advances in eco-friendly green materials are discussed, with a focus on using bio-based, recycled, or recyclable components to reduce environmental impact while maintaining mechanical performance. Driven by environmental regulations and cost savings, these designs aim for greener transport and building solutions. Studies on bio-based green sandwich structures [49,50], natural fibers [51], wooden cores, and recyclable materials reveal their promising advantages. Innovations in 3D printing and thermoplastic adhesives are encouraged to enhance products recyclability and performance. A review of balsa wood cores [52] highlighted their sustainability and mechanical properties, but variation in properties, manufacturing challenges, and in-service performance issues need further research.

Some reviews highlight the evolution, challenges, and applications of sandwich structures in aeronautics, highlighting their complexity in design, manufacturing, and certification. Thus, getting through challenges in design and fabrication, ongoing research for improved aeroelastic performance is focused on optimization techniques under flutter constraints [53–55]. In addition, a comprehensive review presented damage-detection methods for composite structures, Non-Destructive Inspection (NDI) techniques, vibration-based methods, and advanced approaches like vibro-acoustic modulation and ML [56]. It highlights the importance of early damage detection, smart composite structures, and future research directions in SHM.

Several literature reviews address optimization problems, focused on the use of ML-based algorithms for composite structures [57–59]. Nikbakht and Kamariana [60,61] comprehensively examined optimization studies on laminated, sandwich, and functionally graded structures conducted since 2000. The study was focused on enhancing mechanical and thermal properties, such as buckling resistance, stiffness, and strength, while minimizing weight, cost, and stress by categorizing the structure type (beams, plates, shells, etc.). The article discussed design variables such as stacking sequences, objective functions (e.g., maximizing buckling load or minimizing weight), and widely used techniques like GAs and PSO.

However, while many review papers have explored the optimization of composite structures, there is a significant gap focusing on a review for the optimization of sandwich constructions, particularly in terms of structural characterization, advanced analytical and numerical simulations, reliability analysis, and experimental validation of results. This article attempts to address this gap by analyzing the rapidly growing research interests in sandwich structures in recent years, as evident from Figure 3. This article emphasizes key aspects such as optimization algorithms, objective functions, loading conditions, design constraints, design variables, numerical simulation tools, and validation schemes of various optimization studies. The study proves to be an organized literature review categorized into structural elements (plates, beams, shells), optimization procedures and innovative core developments (3D-printed cores, auxetic cores, lattice cores). It also encompasses the optimization studies relevant to dynamics/vibration damping, acoustics performance, energy absorption/impact response, and SHM. Furthermore, it highlights application-based optimization efforts in aerospace, marine, and automotive industries, with a particular focus on ML and GA-based techniques.

5. Advanced Analysis and Optimization Procedures of Composite Sandwich Structures

The development of simple and practical methods for predicting the design parameters of composite sandwich structures under various loading conditions is significant for the computational efficiency of optimization algorithms.

Su and Liu [62] proposed an efficient structural optimization model to calculate wrinkling stresses in sandwich structures under in-plane compression. A minimization problem for wrinkling stress was formulated and solved by dividing the core into artificial plies, each with a corresponding coefficient. The buckling deformation was used as the design constraint, and the strain function ensures that the wrinkling occurs in the facesheets. The proposed methodology was validated using a Finite Element (FE) simulation of the sandwich panel consisting of Glass Fiber-Reinforced Polymer (GFRP) facesheets and a polyurethane foam core. DorMohammadi [63] presented a multiscale optimization framework based on micro- and macro-level material models by designing composite sandwich plates of Carbon Fiber-Reinforced Plastic (CFRP) facesheets and an Al honeycomb core. Multiple failure modes like global buckling, shear crimping, intercellular buckling, and face sheet wrinkling were used as design constraints under various edge loading conditions. The strategy of combining multilevel optimization with proper coordination resulted in a substantial reduction in the computational cost. Luo [64] investigated a sandwich structure with an Al-based non-uniform Bezier curve-walled rectangular honeycomb core. A multi-objective optimization methodology using a Non-Dominated Sorting Genetic Algorithm (NSGA-II) was utilized to minimize weight, deflection, and maximize buckling load. Furthermore, the Parabolic Shear Deformation Theory was used for structural analysis.

Li [65] studied the Minimum Potential Energy Principle for buckling analysis of CFRP fluted-core sandwich panels subjected to uniform compression with simply supported and clamped boundary conditions. An analytical model was developed according to the Classical Laminate Plate Theory (CLPT) and the Rayleigh–Ritz method. The effect of geometric parameters, such as thickness of facesheets, fluted core web thickness, angle and height, and aspect ratio, on the buckling behavior of the panels, was analytically investigated and verified with experiments. Seyyedrahmani [66] developed a multi-objective optimization framework for a sandwich structure made of GFRP facesheets and a glass-epoxy core. The study optimized the lamination parameters (i.e., stiffness properties of the facesheets and core). The elaborated method used GAs and First Order Shear Deformation Theory (FOSDT) to maximize buckling load and fundamental natural frequency while minimizing the cost. Sjolund [67] proposed a discrete optimization procedure for a sandwich structure made of GFRP facesheets and balsa core to minimize total mass while satisfying displacement and buckling constraints. The discrete parameters to be optimized are the material selection and the thickness of facesheets, as well as the core. A novel thickness parameterization rather than constitutive properties allows simultaneous optimization of the core and facesheet layers, which ensures symmetric layup to avoid warping during curing.

Kovács [68] optimized a novel multicellular plate structure made of CFRP facesheets and pultruded GFRP square hollow section stiffeners by utilizing the Flexible Tolerance Optimization (FTO) method. Design constraints were the deflection, stresses, and buckling, while simply supported boundary conditions were used under a uniformly distributed load. A comparison of the optimization results was made with sandwich structures consisting of (a) CFRP facesheets and Al stiffeners and (b) steel facesheets and steel stiffeners. Liu [69] presented an analytical model for predicting failure mechanisms and optimization of a novel curved composite sandwich structure made of GFRP facesheets and a polyurethane foam core under bending load. A multistage filament winding technique was used to manufacture the structure. The results showed that the core web design played a critical role in the deformation and failure modes of the structure. Hu [70] presented a study to compute the bending stiffness of a composite grid sandwich beam structure made of bidirectional GFRP facesheets and a functional foam core using FOSDT. Optimal parameters like stiffener thickness, distance between the stiffeners, and fiber lay-up angle were achieved to enhance the bending stiffness.

Gaydachuk [71] presented a multistage weight minimization algorithm for a shell-type sandwich structure made of CFRP facesheets and a Nomex honeycomb core under transverse forces and bending moments. The method achieved minimum weight while ensuring load-bearing capacity. Furthermore, the model was validated through strength tests. Dobos [72] carried out process optimization of fused deposition modelling for multilayered sandwich specimens (ISO-178 standard [73]) using poly lactic acid material. Optimal parameters of infill density, pattern, and layer thickness were achieved to maximize specific load capacity. A gradient-based optimization approach was used via ANSYS Workbench 2022 R1 for simulation. The optimal filling density and pattern were used to efficiently utilize 3D-printing equipment with reduced run time and material consumption. Yuan [74] proposed a methodology using a Honeybee-inspired Nest Site Selection Optimization algorithm to optimize the first failure load of unidirectional fiber (glass, graphite, or aramid) facesheets and balsa wood core doubly curved sandwich shells. The model used the Tsai–Wu failure criterion, the Third-order Shear, and the Normal Deformable Plate/Shell Theory. Optimal designs for clamped and simply supported shells under uniform normal pressure and uniform tensile traction loads were determined. Effects of uncertainties in material parameters were quantified using the Latin Hypercube Method.

Gao [75] proposed a multi-objective optimization surrogated model, based on Response Surface Method (RSM) for a sandwich structure made of a GFRP facesheet and polypropylene honeycomb core and thermoplastic adhesive film to maximize Specific Energy Absorption (SEA) and minimize the Pareto front. Experimental and numerical analysis validated the optimization results. Sun [76] presented a parametric study using commercial Al alloy A5052 facesheets and a honeycomb core sandwich construction to characterize the crashworthiness behavior under three-point bending and in-panel compression. The study was validated through the FE model and a series of experiments. Castañeda [77] carried out the optimization of CFRP facesheets and a polyurethane foam core sandwich beam using higher-order beam theories and an N-objective optimization evolutionary technique under bi-sinusoidal transverse pressure. Beam models were developed in the framework of the Carrera Unified Formulation, and governing equations were derived from the Principle of Virtual Displacement. The approach reduced computational costs and presented refined models through the Best Theory Diagram.

Cinar [78] introduced an optimization-based approach to characterize the modal behavior of a sandwich construction made of CFRP facesheets and a Nomex honeycomb core using the GA available with MATLAB 7.2 toolbox. The approach minimized the objective function as the sum of the squares of the differences between the lowest five natural frequencies of the structure to determine accurate 2D equivalent models. Due to the absence of cellular structures in the model, it could not be utilized for the stress and collapse analysis of structures. Hui [79] optimized a novel sandwich structure consisting of CFRP facesheets and an egg-shaped chamfered-walled honeycomb grid core using the 2D pseudo-equivalent model and variation asymptotic method. The computed dynamic response in terms of natural frequency and vibration was validated experimentally using sandwich panels made of an Al core. Demircioğlu and Bakır [80] proposed a hybrid approach combining a Deep Learning algorithm and FE analysis to predict delamination growth using the Cohesive Zone Model (CZM) in sandwich structures constructed from GFRP facesheets and PVC foam core under a cantilever boundary condition. The model used Bayesian optimization to update the Gaussian Process model with the dataset through FE simulations. The FE simulation model induced a wide range of delamination sizes to assess their growth and influence on the corresponding natural frequencies.

Koutoati [81] studied an analytical model to determine the static and free vibration behavior of FGM sandwich beams with a viscoelastic core, using the Asymptotic Numer-

ical Method combined with Timoshenko's First Order and Reddy's higher-order shear models to solve the nonlinear, frequency-dependent stiffness matrix. The optimization algorithm focused on efficiently computing damping properties, eigenfrequencies, and loss factors, which were validated through ABAQUS simulations. The model demonstrated sensitivity to the power law index and boundary conditions. Yarasca [82] developed a refined equivalent single-layer plate theory using the Axiomatic/Asymptotic Method and GAs to build Best Theory Diagrams for simply supported sandwich plates subjected to bi-sinusoidal transverse pressure. The model used an N-objective GA and Carrera Unified Formulation to achieve Layer-Wise accuracy with fewer variables. The plate analytical model used polynomial, Maclaurin, high-order zigzag, trigonometric, exponential, and hyperbolic expansions to accurately predict displacements and stresses. The method was based on the principle of virtual displacement, and Navier-type closed-form solutions were obtained and validated through benchmarks. Li [83] discussed the weight optimization of a grid shell sandwich structure made of aluminum for an autonomous underwater vehicle under hydrostatic pressure. The optimization model used a Genetic Algorithm-based Back Propagation NN surrogated model, and the PSO was used for improving model accuracy. Kovács and Farkas [84] used an analytical optimization algorithm to minimize the cost and weight objective functions of a sandwich structure consisting of CFRP face sheets and a polystyrene foam core. The optimization problem was solved for deflection, stress, eigenfrequency, and thermal design constraints. Bai [85] investigated temperature effects on the modal characteristics of a sandwich structure constructed from CFRP facesheets and a Nomex honeycomb core. Thermal characterization of natural frequencies and modal damping ratios had been carried out using experimental and FE analysis. The study showed that temperature-dependent material properties play a major role in the variation of modal parameters. Severson [86] introduced novel selection charts designated as Moment Index numbers used for optimizing the CFRP facesheets and Al honeycomb core sandwich structures. The charts were used to define the number of plies, stacking sequence, core thickness, and density based on the moment-carrying capacity. Furthermore, this was validated by measurements according to the ASTM D7249 standard [87]. The study used novel 3D FE modelling, and the core explicitly used 2D elements of a linear-elastic isotropic model with bilinear isotropic plasticity.

6. Optimization of Innovative Core Structural Elements

The topological parameters of cores, including their structure, thickness, number of core layers (multi-core sandwich construction), core wall thickness, and material, have been investigated by researchers. The choice of core materials governs the overall mechanical performance of the sandwich structure. In this section, optimization studies for various core types, including foam, honeycomb, lattice, corrugated, and bio-inspired cores, as well as their materials, are discussed. These studies examined how different core configurations influence the performance of sandwich constructions and the efficacy of the optimization models. The core parameters that influence the structural performance are the core material (metallic foams, polymeric foams, smart materials, composite cores), the core structure (honeycomb core, corrugated core, truss core, bio-inspired core, functionally graded core, lattice core), the core height, the core wall thickness, and the number of core layers. Figure 5 shows the different cores' geometries to be discussed in the following subsections.

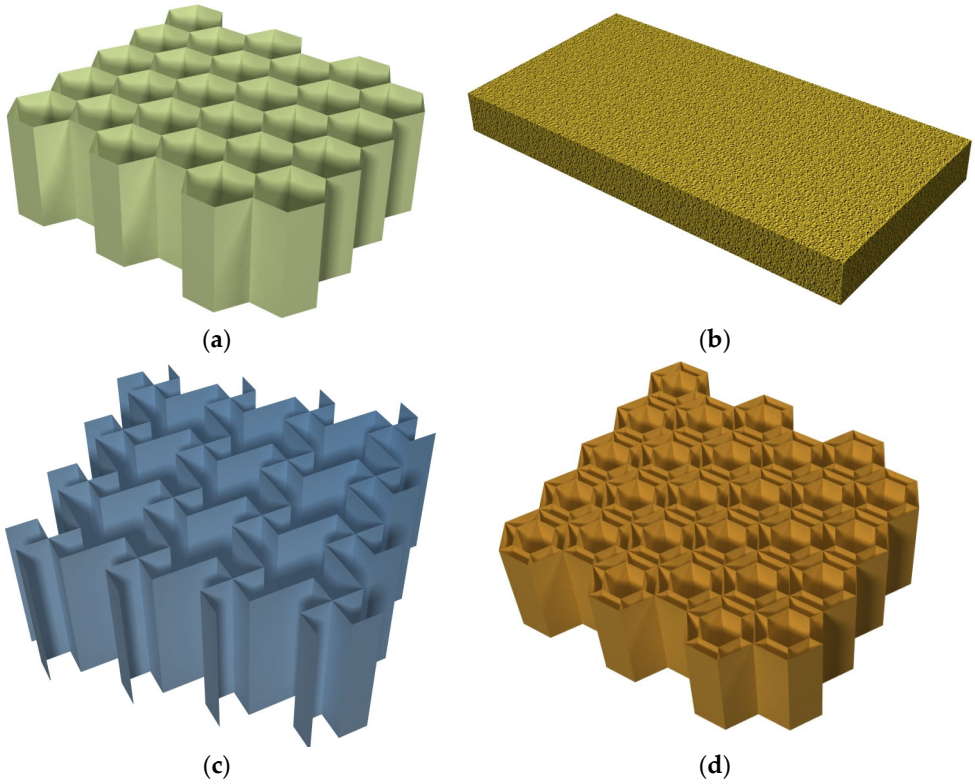


Figure 5. A schematic view of various core structures. (**a**) Honeycomb core; (**b**) Foam core; (**c**) 2D auxetic lattice core; (**d**) Bio-inspired spider web core.

6.1. Optimization Studies of Lattice Cores

Zhu et al. [88] applied the Rational Approximation of Material Properties (RAMP) material interpolation model to calculate the elemental stiffness for 3D-printed isotropic truss-based lattice core sandwich construction. The Method of Moving Asymptotes was used as the optimizer to efficiently compute the relative Young's modulus as a function of relative density. The method enables computationally affordable optimization without considering the rotational degrees of freedom of the lattice. Experimental validation highlights the superior deformation response and mechanical performance of plate-based lattices over truss-based lattices adopted for 3D printing. Meng [89] introduced a novel inverse approach based on the experimental responses for numerically modelling the 3D-printed epoxy resin (SPR600B)-based lattice core sandwich structure. The model used variable cross-section beam elements for numerical investigation, and results were validated experimentally and numerically using solid elements-based simulations. Fan [90] optimized a novel functionally graded lattice core sandwich structure by varying the porosity distribution pattern under bending load. The study was validated using 3D-printed sandwich panels made of commercial α-SiC ceramic powder and SiO_2 hollow microspheres as raw materials, with epoxy resin used as a binder and phenol formaldehyde matrix. The study revealed that the mechanical properties were improved by optimizing the pore gradient distribution.

Atabakhshian [91] studied the topology optimization of Al lattice-core sandwich beams for energy absorption under low-velocity impact to maximize SEA. The model utilized the Solid Isotropic Microstructure with Penalization (SIMP) method along with ABAQUS FE simulations to optimize the lattice-core orientation. Nasrullah [92] studied various lattice core structural configurations for the crashworthiness parameter (i.e., SEA) to identify the octet lattice structure as the optimal. Furthermore, a topology optimization of an octet lattice core was executed using the Altair Inspire software to refine the unit cell

lattice parameters. The optimal octet lattice core used in an aircraft subfloor structure was validated via a simulation using the LS-DYNA R11.2.0 FE software in the case of ground collision load.

Hooshmand [93] studied 3D-printed polyethylene-based lattice core structures to predict strain using five supervised ML algorithms with regression models. The method was based on lattice parameters (type, cell size and wall thickness), and the SHAP method was used to evaluate feature importance. The study used nTop Simulation module to design the core shapes under various loading conditions. The model was evaluated based on Mean Squared Error (MSE), Root Mean Squared Error (RMSE), and Mean Absolute Error (MAE) during training and testing phases to compare the performance via a Taylor diagram. Daynes [94] presented a novel topology optimization methodology for functionally graded lattice core structure using Altair's OptiStruct 2017 software, which uses the SIMP method along with the Method of Feasible Directions (MFD) optimization algorithm. The objective function of the study was to minimize the structural compliance function, which is the measure of the elastic strain energy. Integrated panels were manufactured using 3D printing with powdered material polyamide PA 2200 (Nylon 12). The study presented an integrated optimization and manufacturing scheme resulting in a smooth lattice region with better strength and aesthetics. Hwang [95] optimized the hybrid lattice core (containing solid struts and polymer foam) unit cell without considering the facesheets of sandwich structures. The study was focused on minimizing the unit cell density under compressive and shear strength constraints using an analytical optimization model. The results revealed that tetrahedral cores without foam are the most efficient configurations in combined loading conditions.

6.2. Optimization Studies of Honecomb and Foam Cores

Xiang [96] explored the development of Carbon Fiber-Reinforced Polyetheretherketone honeycombs using multispot ultrasonic welding. The addition of Multiwall Carbon Nanotubes enhanced the interfacial strength, crushing stability, and energy absorption, resulting in a lightweight alternative to traditional honeycombs. Rajput [97] investigated a sandwich structure made of an Al honeycomb core for energy absorption under low-velocity impact using experimental and numerical methods. To determine the effect of honeycomb core foil thickness, cell size, and core height on specific energy absorption, the Latin Hypercube Sampling (LHS) method was used to gather the samples and this was analyzed using ABAQUS FE simulations. Furthermore, polynomial regression models were generated to be used as fitness functions for optimization by incorporating a PSO algorithm in MATLAB, to maximize SEA. Vakilifard [98] investigated the bending properties of five-layer sandwich panels with three layers of corrugated cores at $0^\circ/90^\circ/0^\circ$ and $90^\circ/0^\circ/90^\circ$ orientations, made of Al alloy, using numerical, experimental, and analytical methods. A GA was used for optimizing the weight and height of the structure, constraining the maximum deflection. The results revealed that the orientation of external and internal cores plays an important role in achieving the optimal solution.

Xie [99] established an equivalent solid model of an Al honeycomb structure using RSM to achieve maximum SEA. The model used the response surfaces constructed using the LHS method and ANSYS/LS-DYNA FE simulations to achieve the optimal parameters of the honeycomb. Zhou [100] introduced an efficient data-driven optimization framework to design novel Al polyline/curved hexagonal B-spline honeycomb for sandwich constructions using Deep Neural Networks and Genetic Algorithms to achieve maximum SEA. The method utilized a Python 3.9 script to train four Deep Neural Network (DNN) models for predicting the relative density, peak crushing force, mean compression force, and SEA. The model used LS-DYNA FE simulations using a piecewise linear plasticity material model

and was validated through the quasi-static compression tests. Zhang [101] proposed a multi-objective optimization algorithm to investigate sandwich circular tubes made of an Al foam core with a V-shaped boundary condition under lateral blast loading. The model used a combination of the RSM (LHS) and Multi-Objective Genetic Algorithm (MOGA) to obtain the Pareto fronts for minimizing mass and deformation while maximizing SEA. The FE simulations were carried out by using the ABAQUS explicit solver, and the results were validated through lateral blast experiments on samples.

Ebrahimi [102] proposed a single- and multi-objective optimization model for sandwich cylindrical columns made of an Al honeycomb core under axial crushing loads. The model used the PSO algorithm to maximize the SEA and minimize the peak crushing force by comparing the performance of different honeycomb core cell shapes. The meta-models were constructed from the RSM, using cubic basis functions along with FE simulations to obtain Pareto fronts. The model used Sobol's method for sensitivity analysis to define the core parameters. Sadegh Yazdi [103] optimized sandwich panels made of a 3D-printed Polylactide Acid sacrificial honeycomb core and Al front and back facesheets. The model used the Design of Experiments methodology to minimize back facesheet displacement under explosive loading on the front facesheet. A parametric optimization was performed by employing RSM to determine the filling density of the sacrificial core, the geometry of printed honeycomb cells, and the 3D printer nozzle size. The LS-DYNA FE tool was used for numerical simulation, and the results were validated experimentally. Lin [104] optimized a sandwich structure made of a concave arc Al honeycomb core, focusing on anti-blast performance, i.e., to minimize total deflection and maximize SEA. The study investigated different types of honeycomb cores for parametric optimization of honeycomb cells, geometry, and curvatures using ANSYS/LS-DYNA FE simulations and the weapons effect model CONWEP.

Sahib et al. [105] optimized the out-of-plane elastic properties of FRP honeycomb cores using the Representative Volume Element FE model, as well as the Multi-Island Genetic Algorithm (MIGA). The study parametrically optimized the stiffness and shear moduli of the investigated sandwich construction. Li [106] proposed a novel grooved hexagonal Nomex honeycomb core for sandwich structures to prevent bending-induced collapse. An experimental data-driven Gaussian Process was used for a high-fidelity surrogated optimization model to predict the optimal groove parameters (spacing, angle, depth). The proposed algorithm showed an efficient and accurate method for predicting the grooving spacing with a small amount of training data.

Kerche [107] presented the optimization of Z-pin (pins inserted perpendicularly to enhance stress transfer efficiency and core-skin delamination failure) location and angle for a sandwich structure constructed from GFRP facesheets and a foam core with experimental validation. The study used a simple search algorithm (fminsearch) using MATLAB, integrated with the FE model to maximize flexural stiffness. Despite improved mechanical performance and an increase in stiffness with optimal pin angles, results showed manufacturing challenges for angled pins. Djamaluddin [108] optimized a sandwich structure built up from Al facesheets and foam core using the Response Surface Method for optimizing the structure's natural frequency as an objective function to define core and facesheet thicknesses as design variables. FE analysis validated the model, showing that increasing core thickness significantly boosts the natural frequency.

6.3. Optimization Studies of Bio-Inspired/Green Cores

Bio-inspired core structural elements of sandwich constructions are inspired by the evolutionary designs of natural organisms, aiming to enhance mechanical performance and optimize material properties. By integrating biomimetic principles, these structural

elements significantly improve the stability, strength, and overall durability of composite structures when subjected to external stresses and fulfill the recent sustainability requirements. Contemporary, rising environmental concerns and strict anti-pollution regulations are generating a growing interest in green composites. These sustainable materials are designed to be recyclable and eco-friendly, addressing the need for reduced environmental impact. Researchers are increasingly prioritizing the development of these green composites as a viable solution for a more sustainable future.

Zhang [109] presented a comprehensive review on the interdisciplinary design and optimization of honeycomb sandwich structures in macro-, micro-, and nanoscales, emphasizing their applications in aerospace, architecture, energy and biomedical sectors. The study included manufacturing possibilities and performance of bio-inspired honeycomb constructions along with their performance based on mechanical, thermal, and acoustic characteristics. Dashtgoli [110] made an effort to study the behavior of bio-inspired sandwich constructions under quasi out-of-plane compressive loading, with the use of three ML-based models, i.e., Generalized Regression Neural Networks (GRNN), Extreme Learning Machine (ELM), and Support Vector Regression (SVR). The GRNN outperformed the others when compared based on the performance indicators R-squared (R2), MAE, and RMSE. Sandwich panels made from balsa wood facesheets and oak tree cupules as the core were used to verify this innovative methodology. Zuccarello [111] studied a green sandwich structure using sisal-reinforced epoxy facesheets and a balsa core (uniaxial fibrous structure with low transverse shear and compressive strength), focusing on balsa wood core configurations. The experimental validation of the proposed structure was also carried out. The optimization of the sandwich structure was obtained by using a lay-up [$\pm 45^{\circ}/90^{\circ}$] in terms of shear and compressive strength, outperforming synthetic counterparts, e.g., GFRP sandwich structures, in terms of flexural modulus and environmental impact.

Ribeiro [112] presented the multi-objective optimization of sandwich panels with recycled PET foam cores and homogeneous facesheets under impact load using a CZM-based nonlinear explicit ABAQUS FE model, validated via experimental results. NSGA-II was used to evaluate candidate designs for obtaining the Pareto fronts to minimize mass and maximize SEA. Omede and Grande [113] proposed a multi-objective optimization model for a bio-inspired honeycomb cell structure (elytra and bamboo) for crashworthiness using the NSGA-II coupled with FE simulations to improve SEA and Crushing Force Efficiency (CFE). Boccarusso [114] investigated the production and mechanical performance of bi-grid (planar structures with ribs running in various directions to handle multidirectional loads) cores for sandwich structures using CFRP facesheets via a customized manufacturing process. The study presented the optimization of core density to enhance flexural, compressive, and impact properties. The results demonstrated superior energy absorption and reduced damage under impact, highlighting the potential of hemp fibers (vegetable fibers) as sustainable alternatives in structural applications.

Huang [115] proposed a bio-inspired sandwich structure with two different configurations of sinusoidal cores (abbreviated as BSS and BSD) and Al facesheets. BSS core has the same sinusoidal sections in X- and Y-directions, and BSD has different sinusoidal sections in X- and Y-directions. The model used the Polynomial Regression (PR) metamodel and Multi-Objective Particle Swarm Optimization (MOPSO) algorithm. The study used SEA and CFE as objective functions, and core wall thickness as a design variable. BSS has an advantage in terms of the optimal criteria under different loading cases compared with BSD for energy absorption performance. Hao [116] optimized the strength-to-weight ratio of a wood-based sandwich structure, using medium-density fiberboard as the facesheet and a paper-based honeycomb core under quasi-static load. The results revealed that adjusting skin and core thickness, while fixing materials, achieves the highest strength-to-weight

ratio. Specimens with a core in a perpendicular direction have shown better load resistance than in parallel to the facesheets. Gopalan [117] investigated the vibration characteristics of a biodegradable sandwich beam of jute/epoxy face sheets and a polypropylene honeycomb core by applying FEA and experimental validation. An optimization study was carried out using Minitab 20.1 software based on a Regression Equation for the first three fundamental vibration modes to achieve the optimum parameters, i.e., core thickness, number of layers, and fiber orientation.

7. Optimization Studies of Composite Sandwich Constructions

Structural performance-related optimization studies on sandwich structures (constructed from facesheets and core) are broadly categorized based on specific loading conditions, such as stability under buckling load, impact absorption, bending stiffness, dynamic load and vibration damping. Furthermore, several other studies involve geometric and functional optimization, where topological methods are used to optimize material distribution within the core and the facesheet. However, performance-based optimization frameworks are focused on specialized characteristics such as acoustic properties, where key parameters like Sound Absorption Coefficient (SAC) and Sound Transmission Loss (STL) are commonly used as primary optimization objectives. These diverse optimization approaches reflect the growing need to address both structural integrity and functional performance in modern sandwich constructions.

Furthermore, efficient optimization algorithms for sandwich constructions reduce the computational time and cost for topology optimization, acoustic performance and optimal structural design under various loading conditions, i.e., buckling load, impact load, bending load, vibration/dynamic loads, etc. In this section, various optimization studies relating to sandwich constructions are discussed for different objectives in the case of different design constraints and variables.

7.1. Topology Optimization of Sandwich Structures

Zhang [118] developed a variable-density topology optimization method for curve-walled square honeycomb sandwich structures using the high-order RAMP interpolation model. The proposed model used the Bidirectional Evolutionary Structural Optimization (BESO) algorithm to refine the optimality criteria. The model was validated through numerical simulations and experimentally by the three-point bend test of sandwich structures made of CFRP prepreg facesheets and 3D-printed photosensitive resin core. Larsson [119] introduced a topology optimization scheme for core and facesheet thickness combinations using Mixed-Integer Linear Programming to minimize the total mass of a sandwich structure subjected to static and dynamic constraints. The methodology was validated for a centrally loaded, long, slender sandwich beam made of GFRP facesheets and a polymer foam core, clamped at both ends. Larsson [120] elaborated a novel mixed linear extension of the Topology Optimization of Binary Structure method for sandwich beams, combining core topology and facesheet thickness to minimize total mass under a given compliance function. The optimization problem was solved using an open-source solver called "COIN-OR CBC23" through the Python interface module "cylp". Furthermore, the methodology was validated for a centrally loaded clamped sandwich beam. Xiao [121] proposed a multi-scale topology optimization method for a graded lattice sandwich structure to optimize the facesheet thickness and lattice distribution within the core. The methodology was based on constructing a kriging metamodel for property estimation of lattice cells. The method was validated for a 3D-printed clamped, centrally-loaded sandwich beam structure for mass minimization and natural frequency maximization.

Li [122] introduced a 2D and 3D multiscale topology optimization method combining the Bi-directional Evolutionary Structural Optimization method and SIMP for the optimization of sandwich structures at macro and micro levels. The model was validated for 3D-printed beams using HD photosensitive resin materials for load bearing, stiffness, and energy absorption characterization. Ding [123] developed a multiscale topology optimization method for asymmetric porous sandwich structures, optimizing facesheet thickness and material, as well as composite core configuration to minimize structural compliance. A Difference Set-based Multi-Material Level Set model was applied to represent the topology of each material phase within the sandwich core. Several 2D and 3D numerical case studies with different material configurations and boundary conditions demonstrated the effectiveness of the methodology. Chu [124] proposed a novel topology optimization method for designing sandwich structures with truss cores using a Moving Morphable Components framework and a Multi-Component Topology Description Function. The method transformed the topology optimization problem into a parameter optimization problem with fewer design variables, enabling explicit geometric representation. The study was validated using 2D and 3D numerical examples, and the results were compared with hexagonal honeycomb core sandwich panels.

7.2. Optimization of Sandwich Structures for Buckling Load

Quang [125] investigated the static buckling of a sandwich structure constructed from magneto-electro-elastic facesheets and a auxetic honeycomb core using Reddy's HOSDT and the Galerkin method. The Bees Algorithm was applied to maximize the critical buckling load for five geometrical and material parameters, also considering the effects of elastic foundations, temperature, and initial geometrical imperfections. The methodology was validated for simply supported sandwich plates with FGM facesheets and a homogeneous core layer under uniaxial compression. Abouhamzeh [126] optimized the buckling load of sandwich cylindrical panels made of FRP facesheets and an Al honeycomb core using a GA available in the MATLAB toolbox, coupled with FE simulations. The study was focused on optimizing fiber stacking sequences and core thickness, demonstrating the GA's effectiveness for structural performance under in-plane loading.

Schultz [127] explored the optimization of a composite sandwich shell structure made of FRP-based outer/inner shells and an Al honeycomb core used for launch vehicles, applying the PANDA2 design optimization tool. The model analyzed the NASA Shell Buckling Knockdown Factor and the structural weight. Additionally, buckling imperfection sensitivity of the optimized designs was explored using nonlinear FEA and the measured shape of a large-scale composite cylindrical shell. Njim [128] optimized a functionally graded sandwich plate with porous polymer homogenous facesheets and an Al core using Multi-Objective Genetic Algorithm (MOGA), Design of Experiment (DOE), and RSM to maximize buckling load and minimize deformation. The mathematical model was based on the Classical Laminate Plate Theory, and the experimental validation was carried out using 3D-printed samples under compressive loading.

7.3. Optimization of Sandwich Structures for Dynamic Load

Cao [129] optimized the FRP sandwich plate structure with a viscoelastic square honeycomb core, utilizing MOGA to minimize the transient response peak, vibration decay time, and the reciprocal of overall stiffness. The optimization problem was solved based on the minimum strain energy principle and the Nemark-β method variables. The design variables include fiber laying angles, core thickness ratio, and modulus ratio, with PF solutions balancing vibration resistance and structural stiffness. Zheng [130] optimized a multilayer damping sandwich composite open cylindrical shell made of CFRP, based on the free

vibration model using the Rayleigh–Ritz method and FOSD shell theory. The model solved the free vibration equations under four-sided simply supported boundary conditions for the natural frequency and loss factor of the structure under different numbers of core layers. Xu [131] proposed a nonlinear damping prediction model for FRP-based, partially filled honeycomb core sandwich structures using a theoretical approach, integrating HOSDT and Hamilton's principle. The study used FEA to deduce the energy equations, and the complex modulus method was used to obtain nonlinear damping to optimize the filler density, honeycomb cell thickness, and panel thickness. The results were validated with test specimens through vibration testing for the cantilever structure.

Dong [132] proposed an analytical model using the Rayleigh–Ritz method and Nemark-beta algorithm to optimize the free and forced vibration behavior of sandwich cylindrical shells with corrugated-honeycomb cores and functional gradient composite facesheets under thermal and mechanical loads. The study optimized the core configurations and skin material for vibration damping using FOSDT, the Green heat strain hypothesis, and the spring simulation technique under arbitrary boundary conditions. Choi [133] optimized a sandwich structure made of CFRP facesheets and foam core using the Equivalent Static Load Method, under dynamic loads and clamped boundary conditions to minimize weight and maximize stiffness and strength. Impact load, sinusoidal bending load, and ramp-step bending load were applied to three types of sandwich composite structures with a foam core, honeycomb core, and sinusoidal honeycomb core. The thickness and angle of the facesheet plies were used as design variables. Kim and Park [134] proposed an optimization method using the Ritz formulation to design a composite sandwich structure with a passive vibration absorber for satellite applications, focusing on minimizing mass and maximizing vibration damping. The optimization scheme was implemented in MATLAB for a sandwich structure consisting of CFRP layers, a honeycomb core layer, a solar cell layer, and a cover glass layer.

Madeira [135] used a derivative-free multi-objective optimization solver, the Direct Multi Search method, to optimize the placement of Constrained Layer Damping patch treatments on the surface of the laminated plate, with a viscoelastic core and anisotropic laminated facesheets. The model was validated for L- and T-shaped clamped plates, aiming to minimize weight and maximize modal damping as Pareto fronts to show trade-offs between added mass and damping performance. Song [136] proposed a hybrid optimization approach that combines the Rayleigh–Ritz solution with the penalty method on Thin Plate Theory to analyze the dynamic responses of sandwich plates with viscoelastic cores and isotropic facesheets under moving loads. The study obtained the governing equations of motion through the Lagrange equation. Furthermore, boundary conditions were derived based on FSDT. The method was used to determine the influences of different parameters, such as the constrained layer, damping layer, and base layer, on the natural modes of vibration and dynamic responses.

7.4. Optimization of Sandwich Structures for Impact Load

Chen [137] optimized a sandwich structure constructed from CFRP facesheets and Nomex honeycomb core with a multi-objective optimization algorithm based on surrogate modeling using NSGA-II for enhanced energy absorption and weight minimization. The model used the CZM to assess the damage behavior of the structure under edgewise crushing by tailoring the effective height and bevel angle. Qiu [138] introduced a two-stage optimization approach (hybridizing response similarity search) to find the impact load location. The approach is used to minimize the nominal response residual between the reconstructed and actual responses of a sandwich structure made of CFRP facesheets and honeycomb core. The model used the Tikhonov regularization method and the L-

curve criterion to obtain the desired solutions using MATLAB code and was validated through experimentation. Wang [139] proposed a topology optimization procedure for a sandwich structure made of CFRP facesheets and a dual-phase lattice core to enhance energy absorption characteristics. The study utilized a density-based optimization method, integrated with the variable density method SIMP, to minimize structural compliance. The validation was carried out for a sandwich panel with 3D-printed Poly Lactic Acid (PLA) lattice core and CFRP facesheets for the three-point bend test. Deng [140] investigated the ballistic performance in terms of the ballistic limit velocity, deformation modes, energy dissipation mechanisms and specific penetration energy of sandwich panels made of a foam core and homogeneous facesheets under high-velocity spherical projectile impact. The study investigated the effect of structural configurations like a multi-layer, gradient core and asymmetric facesheets on ballistic performance.

Costa and Driemeier [141] proposed a metamodel-based optimization framework using Artificial Neural Networks (ANNs) and Radial Basis Functions (RBFs) with the NSGA-II to optimize lightweight sandwich panels with auxetic-core for enhanced impact energy absorption-to-weight ratio. Metamodeling was used instead of direct optimization with performance evaluation, and the best-ranked model was used for the subsequent optimization of the investigated structure, fixed at its edges and impacted at its center. Pandey [142] carried out multi-objective optimization of a sandwich structure made of CFRP facesheets and an Al honeycomb core to maximize SEA and minimize peak load under low-velocity impact. The study used LS-DYNA-based FE simulation applying a Continuum Damage Mechanics (CDMs)-based CZM model for facesheet damage and delamination, respectively. The model used RSM to build a metamodel for optimizing geometric parameters like the cell size, cell thickness, cell height, and facesheet thickness. Mohan Kumar [143] optimized the ballistic impact response of a jute rubber core-based hybrid sandwich structure using Taguchi's DOE and FE simulations to maximize the energy absorption. The study parameterized the core thicknesses and different filler compositions using various shaped projectiles, like flat, conical, and hemispherical shapes, to maximize the objective function.

Lin [144] optimized a novel multilayer thin-walled sandwich structure based on the Peano space-filling curve using NSGA-II algorithm and RSM to maximize the energy absorption performance. The study was validated through FE simulations and testing of 3D-printed samples for compression behaviors and energy absorption properties. Jiang [145] optimized a sandwich structure made of graded reentrant circular auxetic cored with homogeneous facesheets for blast resistance using a Radial Basis Function surrogate model and the NSGA-II algorithm. The study examined the effects of geometric parameters by generating DOE tables using the Monte Carlo method and a multi-objective optimization algorithm to minimize the deflection and maximize SEA. He [146] studied a sandwich structure with a polyurea-coated auxetic honeycomb core for multi-objective optimization using the NSGA-II algorithm and LS-DYNA FE simulations for polynomial RSM. The parametric optimization for polyuria thickness, blasting center distance, and explosive mass was presented via the Pareto fronts to maximize SEA and minimize deflection.

Qiu [147] proposed a structural optimization method combining a Back Propagation Neural Network (BPNN) and GA to enhance the anti-blast performance of corrugated sandwich plates. By using a BPNN to model relationships and GA for multi-objective optimization, the method significantly improves blast resistance. Furthermore, it was validated using FE simulations. Torabizadeh [148] applied the Taguchi optimization for a sandwich structure made of GFRP facesheets and an Al foam core under low-velocity impact to maximize SEA and minimize the total displacement. The study was used to determine the effect of skin layup sequence, core thickness, and impactor shape (conical,

parabolic, and spherical) on the blast response of the structure. Ali [149] proposed a three-stage combinatorial optimization method for enhancing the crashworthiness of a polyurethane elastomer core sandwich structure. The method utilized the Optimal Latin-Hypercube Design (OLHD), the Radial Basis Function (RBF) surrogate models, and the Multi-Objective Particle Swarm Optimization (MOPSO) to maximize energy absorption and minimize peak crushing force.

Alanbay [150] optimized a sandwich structure consisting of CFRP facesheets and a foam core by applying a surrogate optimization algorithm integrated with FE analysis to minimize structural weight, deflection, and reaction force to enhance the blast-mitigating capabilities. The algorithm optimized the layup of facesheet and foam core thickness using a user-defined subroutine by utilizing MATLAB and the CZM model. Shu [151] obtained the optimal configuration of three-layered corrugated sandwich panels using homogeneous facesheets under crush loading. The study used a multi-objective optimization model NSGA-II combined with RSM to obtain the Pareto fronts for two conflicting objective functions, i.e., initial peak force and SEA. The scheme was validated with the LS-DYNA FE code and experimental results. Hassan [152] optimized a sandwich structure constructed from FRP facesheets and a lattice/honeycomb core by adding carbon nanotubes with a mathematical optimization software, GAMS, to balance cost and energy absorption. The study was focused on design variables like the core structure (octet vs. honeycomb), the hybrid fibers (carbon-Kevlar), and the carbon nanotubes.

Wang [153] carried out single- and multi-objective optimization for a sandwich structure built from CFRP/metallic facesheets and homogeneous (uniform) and graded foam core combinations under blast loading using Kriging surrogate models and the NSGA-II algorithm. Single-objective optimization was used to minimize the peak deflection, while multi-objective optimization for the graded structure aimed to minimize the structural weight and peak deflection. The optimization methods were validated using LS-DYNA FE simulations and experimentation. Lurie [154] presented a parametric optimization model for sandwich shell construction made of GFRP outer and inner shells, and corrugated metallic core, using a multi-scale approach. The model used asymptotic homogenization to evaluate effective stiffness, stress states, stability, and material failure under impact. Polymer foam and Rockwool fibrous insulation were used in the internal space of the core. Lan [155] optimized a cylindrical sandwich panel with a double arrow auxetic core and homogenous facesheets for blast resistance using the LHD method, ANN metamodel, and NSGA-II optimization algorithm. An FE simulation model was built using ABAQUS to optimize deflection and mass of the structure in the first phase, and afterwards generated Pareto fronts for reducing the structural deflection and increasing SEA.

Chen [156] carried out a single- and multi-objective optimization of a clamped layered-gradient sandwich panel made of Al facesheets and a foam core under air-blast loading using the Adaptive Response Surface Method for single-objective optimization. For the multi-objective optimization, GA with RSM and RBF surrogate models was used. The model applied a nonlinear simulation using LS-DYNA FE code to maximize SEA and minimize the total deflection and weight of the structure. Zhang [157] proposed a Reliability-based Design Optimization approach by integrating Kriging surrogate models with Monte Carlo Simulation for probability density function to optimize the crashworthiness of tapered bitubal sandwich columns made of Al and foam cores under uncertainties. A single- and multi-objective optimization using GAs, along with LSDYNA FE simulations, was used to maximize SEA and minimize mass. Wang [158] parametrically optimized a novel 3D double-V auxetic honeycomb core sandwich panel for blast protection using the LH Design of Experiment model and Gaussian Process Metamodel for improving the algo-

rithm's efficiency. A Multi-Objective Particle Swarm Optimization algorithm, along with ABAQUS/Explicit numerical simulations, was used to optimize weight and SEA.

Chen [159] proposed a multi-objective optimization model using RSM to optimize the core height and cell wall thickness of the honeycomb of a sandwich structure made of CFRP facesheets and Nomex honeycomb core under normal and oblique low-speed impact. The ABAQUS FE code was used with CDM and CZM for delamination prediction. Furthermore, an NSGA-II was utilized to optimize conflicting objectives, i.e., weight and the absorbed energies. Baroutaji [160] optimized circular sandwich tubes with metallic shells and Al foam cores for energy absorption under quasi-static lateral loading using the DOE and validated numerically via ANSYS-LSDYNA FE simulations. The multi-objective optimization model used RSM to achieve the Pareto fronts to maximize SEA and minimize the collapse load with the structural parameters as design variables.

7.5. Optimization of Sandwich Structures for Acoustic Performance

Xu [161] introduced a dynamic three-field Floating Projection Topology Optimization method for vibro-acoustic coupling design in lightweight sandwich structures, maximizing STL under volume constraints. The study used FE formulation with the linear material interpolation scheme. The model's effectiveness and accuracy were verified on representative 2D and 3D numerical examples and validated with impedance tube tests. Liu [162] presented multi-objective topology optimization of lattice structures using the Bi-directional Evolutionary Optimization algorithm combined with linearity scalarization to minimize static compliance and radiated sound power. A mixed displacement/pressure formulation was used to determine the vibroacoustic responses. The results were validated through 3D-printed cantilever beam structures actuated with harmonic force. Shi [163] optimized the acoustic performance of acrylonitrile butadiene rubber cellular honeycomb core sandwich panels, applying a multi-objective NSGA-II algorithm. A progressive impedance method using the multiphysics engineering software COMSOL 6.2 was used, focused on STL in the low-frequency range.

Subramanian [164] optimized a 3D-printed honeycomb sandwich structure filled with nano fillers (carbon black and Al powder) for enhanced acoustic properties by utilizing the Central Composite Design method based on RSM. The model was implemented using Minitab software to achieve an optimal noise reduction coefficient across low, mid, and high-frequency ranges. Furthermore, the model's reliability was tested using the Analysis of Variance (ANOVA) method. Zhu [165] proposed a multi-cellular element coupling optimization method to enhance low and medium-frequency broadband sound absorption in ship engineering to minimize the structural weight and improve the Sound Absorption Coefficient. FE simulations were used to analyze the sound absorption characteristics, and the Helmholtz resonance cavity was arranged with multi-cell elements to form an acoustic sandwich structure. The 3D-printed acoustic specimens were used to verify the simulation results experimentally. Li [166] developed a micro-perforated sandwich plate with a corrugated and auxetic honeycomb hybrid core for low-frequency noise reduction, using Classical Sound Absorption Theory and FE simulations to validate the model. A standard GA was used to optimize the structural (upper panel thickness and corrugated wall thickness) and micro-perforation parameters to maximize the SAC.

Liang [167] parametrically optimized a composite multi-cell sound absorber by combining micro-perforated panels, porous material, and air cavity layers using the COMSOL FE model and validated it with experiments using the Impedance Tube Method. The model utilized the Transfer Matrix Method and GAs to maximize SAC in the mid-frequency range with the optimal combination of the structural parameters of the cell. Li [168] studied the acoustic optimization design of porous sound-absorbing foam core sandwich constructions

to mitigate flow-induced vibration noise (for high-speed trains) due to the outside turbulence boundary layer. The model utilized Biot's Theory for material modelling and the modal superposition method to compute STL. A multi-objective optimization model used Isight and MATLAB version 2014b software by applying the NSGA-II algorithm to optimize the bonded-air configuration to obtain the Pareto fronts. The model maximized STL while minimized structural mass based on flow velocity, material thickness, and density as design variables. Mazloomi [169] optimized the vibroacoustic performance of a novel gradient shape auxetic core for sandwich panels (ABS material) using a hybrid GA and Method of Moving Asymptotes model. The study integrated an ANSYS homogenized FE model with the MATLAB optimization toolbox to minimize the Root Mean Square Level of radiated sound power and structural mass. The model used internal cell radii in the different regions, core thickness, the ligament thickness, and the skin thickness as design variables.

Ren [170] optimized the vibro-acoustic performance of trapezoidal corrugated core sandwich construction using a Wave-based Method and FE simulations with Rayleigh's integral to obtain the radiated sound power from the vibrating system. The model was implemented using MATLAB with a GA to maximize average STL in low, middle, and high-frequency ranges. A statistical analysis was used to calculate the coefficient of determination. Furthermore, the model was validated by a sound insulation test using Al samples. Araújo [171] optimized a sandwich construction made of CFRP facesheets and viscoelastic core using active control with piezoelectric sensors and actuators, to minimize radiated sound power, added mass, and number of controllers. The multi-objective optimization mode utilized the Direct Multi Search algorithm. The elastic and piezoelectric layers were modelled with First Order Shear Deformation Theory (FSDT), and the viscoelastic core with Higher-order Shear Deformation Theory (HSDT). Furthermore, the FE simulations were used to obtain the Pareto fronts. De Melo Filho [172] optimized the anisotropic stiff foam core sandwich panels using a resonant metamaterial model to enhance noise insulation by embedding resonators in the foam core. The optimization scheme used the GA of the HEEDS MDO 2019.2. software and FE model to predict the STL of the metamaterial sandwich panel and maximize insertion loss. An experimental validation of the model was carried out by using polymethyl methacrylate material resonators.

Yang [173] optimized a sandwich beam structure with trapezoidal corrugated cores by using a Spectral Element Method and Rayleigh's integral to calculate the transmitted sound power. A GA-based multi-objective parametric optimization model, MIGA, was used to minimize transmitted sound power in a specified frequency band by limiting the structural weight and fundamental frequency. Xu [174] explored a multi-objective optimization model for lightweight sandwich panels to maximize the weighted transmission loss average and minimize structural weight. The NSGA-II was used to obtain the Pareto fronts for optimizing the geometrical parameters, along with the experimental validation of results using a polymer foam core. Galgalikar [175] optimized a sandwich panel with in-plane oriented (load was parallel to the plane of the unit cell) honeycomb core to maximize sound transmission loss by adjusting unit cell geometric parameters (cell wall angle, number of horizontal/vertical cells). The model used a multi-objective NSGA-II algorithm available in the MODEFRONTIER 4.3.0 software. A parametric automated model was constructed using a Python script to integrate an ABAQUS FE model for the Design of Experiments and Response Surface Method, resulting in Pareto fronts for conflicting objectives.

8. Optimization of Sandwich Structures (Case Studies and Applications)

Sandwich structures have become an essential part across multiple engineering sectors due to their exceptional characteristics, including lightweight characteristics, superior en-

ergy absorption, effective vibration damping, excellent thermal insulation, and outstanding acoustic performance. These unique properties enable their adoption in critical applications such as aerospace, automotive, energy, and defense sectors. These enormous properties of sandwich constructions enable their use in advanced engineering systems like aircraft fuselages and wing components, high-speed train bodies, automotive panels, and wind turbine blades. The following subsections will focus specifically on recent optimization research for aerospace and automotive applications, where weight and cost reduction and performance improvement are primary aims.

8.1. Optimization of Sandwich Structures Applied in the Aerospace Industry

Dong [176] proposed a topology optimization procedure for a multilayer sandwich aircraft slat structure made of CFRP facesheets and an Al honeycomb/foam core under the bird strike impact load to minimize the overall compliance function (max. stiffness, min. cost). The optimization model used an ABAQUS FE simulation and the Method of Moving Asymptote for the optimal material arrangement of slit structure. The construction was based on evolutionary principles observed in biological skeletal structures, and further validated through a smooth particle hydrodynamics bird striking test. Rekatsinas [177] presented a road map for the multi-disciplinary optimization of a composite unmanned ariel vehicle's sandwich construction made of CFRP and a foam core to minimize the structural weight. The model used Computational Fluid Dynamic simulations for aerodynamic analysis and FE simulations for structural analysis. The model utilized Altair Optistruct 2021 software with a gradient-based dual optimizer and programming-based approach, i.e., Sequential Quadratic Programming or Separable Convex Approximation, to minimize the Von Mises stresses. Morovat [178] introduced a novel methodology for the Multi-disciplinary Design Optimization of Independent Subspace for FRP composite sandwich fairing structure of a launch vehicle by using independent subspaces. The optimization model used the Simplex algorithm and Fixed Point Iteration method as an iterative process. FE simulations were based on higher-order theories, and under buckling load and external vertical pressure were used to minimize structural weight and cost.

Meddaikar [179] proposed a preliminary optimization approach for a sandwich panel made of CFRP facesheets and a Nomex/Al honeycomb core of a Common Research Model wing. The model used Reissner–Mindlin Plate Theory and the Angle Minus Longitudinal model for material failure. A Python-based optimization framework and MSC NASTRAN FE solver's design and sensitivity module SOL 200 were used to minimize the weight as the objective function. Liu [180] built a model for the topology optimization of a sandwich structure of a solar unmanned ariel vehicle's wing rib made of CFRP facesheets and a Nomex honeycomb core to reduce total weight, using the ABAQUS FE equivalent model. The model used a Python-based Graphical User Interface and variable density method for topology optimization under static loading, validated through experimental tests. Kim and Park [181] proposed a Multi-disciplinary Design Optimization framework combining Reduced Order Modeling, Automated Machine Learning, and surrogate models to optimize the weight of an aircraft's composite sandwich wing structure made of CFRP outer/inner skins and a foam core. The model used snapshot data collection for the initial experimental points using the Uniform Latin Hypercube method. The commercial packages FLUENT and ABAQUS were used for flow-field analysis and structural nonlinear analysis, respectively.

Wang [182] proposed a three-step optimization strategy and an equivalent FE model for laminated and sandwich structures of composite wings by using equivalent strength and stiffness focusing on displacement, stiffness, buckling, and flutter constraints. The model for wing stiffness and flutter optimization uses the Class and Shape Function Transformation technique to describe the wing skin thickness for minimizing structural mass. An [183]

developed an optimization framework for a simply supported sandwich structure made of FRP facesheets and honeycomb core for aerospace applications by integrating a two-level gradient-based approximation method and GA to minimize mass and cost. The model used a Branched Multi-point Approximate function optimized with GA and NASTRAN FE simulations. Shirvani [184] optimized a simply supported sandwich structure made of GFRP facesheets and a honeycomb core under out-of-plane pressure using the Niching Memetic Particle Swarm Optimization algorithm. The model used First Order Shear Deformation Laminated Plate Theory for panel deformation to minimize weight under design constraints of buckling and shear resistance of the core, maximum deflection, and yield of the facesheets.

Al-Fatlawi [185] presented a single- and multi-objective optimization of a lightweight honeycomb core sandwich plate using an Interior-Point Algorithm and GA for air cargo containers. The proposed multi-objective optimization model utilized the weighted normalized method applied by Excel Solver and GA solver via the MATLAB program to obtain the Pareto front to minimize the structural cost and weight. Martínez [186] proposed a multi-objective, multi-scale optimization approach using GAs to optimize a bio-based composite sandwich structure made of ramie fiber for both facesheets and a honeycomb core for an aircraft overhead locker to minimize weight and cost. The model coupled a composite structural FE solver with the MOGA optimization tool, Robust Multi-objective Optimization platform to get Pareto fronts. The model used the Representative Volume Element to obtain the material response. Deng [187] proposes a Multi-disciplinary Design Optimization framework for an aircraft radome sandwich structure made of FRP facesheets and a foam core using MOGA. The model integrates performance and mechanical responses by minimizing the Power Transmission Coefficient, and maximizing the Boresight Error. The model utilized the NASTRAN FE solver with Tsai–Wu and maximum stress failure criteria-based structural analysis. The 3D ray-tracing technique and a physical optics-based aperture integration method were used for electromagnetic characterization.

8.2. Optimization of Sandwich Structures Applied in the Automotive Industry

Al-Sukhon [188] introduced a novel multi-scale and multistage design optimization methodology for a sandwich construction made of a functionally graded hexagonal honeycomb core for minimizing the weight and greenhouse gas emissions of hopper cars. The method combined topology optimization using the SIMP method for frame design and GA-based Multiscale Design Optimization to obtain Pareto fronts. The elaborated method was validated under static and dynamic loading conditions using explicit FE simulations applying Smoothed Particle Hydrodynamics in a Fluid Structure Interaction (FSI) software. Kamble [189] presented a parametric optimization methodology for a lightweight sandwich monocoque of the Sports Car Club of America made of FRP prepreg facesheets and an Al honeycomb core. The vehicle structure was tested against the International Automobile Federation Formula 3 loads to minimize weight under static and dynamic loading conditions. The model parametrically optimized the structure using ANSYS. The model was validated through a drop weight impact test as per the ASTM D7136 standard [190] and simulations using the Radioss solver to investigate the characteristics of material plasticity.

Sahib and Kovács [191] proposed a multi-objective optimization method for a sandwich structure for high-speed train floor panels constructed from an Al honeycomb core and different combinations of CFRP, GFRP, and Al layers in the laminated face sheets. The aim of the optimization was the minimization of the total weight and the total cost of the structure. The model used the Neighborhood Cultivation GA to obtain the Pareto front. The model was validated via ABAQUS/CAE FE simulations. Xie [192] optimized a thin-walled composite sandwich tube made of an Al honeycomb core for subway vehicles, using

high-accuracy surrogate models and a Hybrid Particle Swarm Optimization algorithm. The model was used to maximize SEA, Peak Force, and CFE, and was validated through impact and quasi-static tests. LS-DYNA FE simulations and Polynomial Response Surface, Kriging model, Radial Basis Function, and Support Vector Regression were used alternatively to build surrogates. Mean Relative Error was used to measure the local accuracy of the surrogate model, and Root Mean Square Error was used to measure overall optimization model precision. Yoon [193] presented a topology optimization procedure for a periodically repeated solid-void layout in a sandwich panel for high-speed railway vehicles made of an Al core. The model used topology and size optimization to minimize metal solid volume while meeting sound transmission class and core compliance constraints (stiffness-based functions for core). The proposed model used FE acoustical and static analyses for the Gradient-based Optimizer Method of Moving Asymptotes to maximize the Transmitted Loss and minimize panel weight. Molavitabrizi [194] proposed a multi-scale optimization approach for a sandwich structure made of an Al octet truss lattice core for hopper freight railcar floor panels. The model included meso-scale and macro-scale design factors using ABAQUS FE simulations to minimize structural mass, subject to uniformly distributed lateral loads. Salmani [195] proposed a robust framework, V-shape development model (integrated with optimization techniques to enhance the overall performance at different levels of the system by adopting appropriate weighting factors for different design levels) for the multi-objective optimization of a sandwich structure made of FRP facesheets and a viscoelastic core for an automotive floor panel against bending/torsional stiffness, strength design factor, vibration attenuation, and mass minimization. The model used FE simulations, Taguchi-based Grey Relational Analysis, and the ADAMS Multi-Body Dynamics model for optimization. The ANOVA method was used for sensitivity analysis.

Wei [196] demonstrated a Factor Analysis-based Multi-parameter Optimization approach to improve the blast resistance performance of a multilayer honeycomb sandwich structure of light armored vehicles. Gaussian Process Regression was used to construct the response surface of the surrogate model, and NSGA-II was used as an optimizer to obtain the Pareto front. Finally, the Normal Boundary Intersection method was chosen to find the compromised optimal solution. Pratomo [197] optimized a sandwich structure made of an Al foam core and two facesheets, i.e., an Occupant Side Plate (OSP) and Struck Side Plate (SSP), for an armored vehicle under blast impact loading. The method used the Design For Six Sigma methodology to minimize acceleration and structural intrusion of an OSP. The model used a nonlinear explicit FE model, and the CONWEP methodology for blast modelling. The Taguchi method and the ANOVA were used for the model performance analysis.

9. Optimization of Sandwich Structures Using Genetic Algorithms

Sahib and Kovács [198] elaborated a multi-objective optimization method for sandwich structures constructed from a combination of Al, CFRP, and GFRP layers in the facesheets and an Al honeycomb core used in high-speed train floor panels to minimize weight and cost. The model combined GAs, Backpropagation Feedforward Network with the Levenberg–Marquardt training algorithm. The Monte Carlo simulations were used to get the Pareto fronts. Furthermore, an ABAQUS/CAE FE simulation was also used during the structural analysis, and the model performance was evaluated using the Mean Square Error. Fadlallah [199] proposed a novel optimization model, ANN-PSO, which is a combined ANN and PSO model to minimize the weight of a heliostate sandwich structure made of an Al honeycomb core (used for a solar power system to track the sun's position and reflect the sunlight towards the receiver) under several loading conditions. The model used the Levenberg–Marquardt (LM) and the Bayesian Regularization-based ANN training

algorithms to obtain the optimal parameters with minimum MSE. Namvar [200] investigated the design optimization of a simply supported sandwich plate with Al facesheets and a polycarbonate hexagonal honeycomb core, using an improved multi-objective PSO with a Genetic Algorithm to get the Pareto front, for minimizing weight and total deflection. The model used FSDT governing equations of the plate under a uniformly distributed load. Furthermore, a hyper volume quality indicator was used to evaluate model performance. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) multi-criteria decision-making method was used to report appreciable results from the Pareto front curve.

Xiao [201] proposed a model for optimizing a sandwich construction made of CFRP facesheets and an Al auxetic reentrant honeycomb core using a PSO algorithm with a Layer-wise Optimization Approach to maximize buckling load and natural frequency while minimizing mass. The model used a 2D Asymptotic Equivalent Model based on the Variational Asymptotic Method to analyze vibration and buckling. Kermani and Ehsani [202] investigated a multi-objective optimization using GAs and FSDT for a sandwich structure made of FRP facesheets and a hybrid composite grid core, aiming to maximize critical buckling load while minimizing weight and material cost. The design variables were the grid core parameters like material, dimensions, rib spacing, and rib rotation angle. Brendon Francisco [203] proposed a parametric multi-objective optimization model for a composite sandwich tube structure using hybrid carbon-aramid fiber inner/outer tubes and an auxetic reentrant core. The model used a new meta-heuristic multi-objective Lichtenberg Algorithm with RSM to minimize the mass under compression. Furthermore, the Design of Experiment method and the Central Composite Design method were used for the Pareto front. A statistical analysis method, ANOVA, was used for performance analysis of the optimization method. Experimental validation of the method was carried out using samples of Hexcel carbon-aramid fiber inner/outer tubes and 3D-printed poly lactic acid core.

Wong [204] optimized a bio-based sandwich structure made of fiberboard facesheets and a mushroom-based foam core using three different ANN models, i.e., Cascade-Forward Backpropagation Neural Network, Feedforward Backpropagation Neural Network, and Generalized Regression Neural Network, under edgewise compression to improve buckling resistance. The predictive models used LM training, and the performance was assessed via error criteria that include the Coefficient of Determination (R2), RMSE, and MAE. The model was validated with testing of samples, as per ASTM C364, using a Universal Test Machine. Kheirikhah [205] presented a multistage multi-objective optimization method for a sandwich construction made of FRP facesheets and a soft foam core, using an improved high-order three-layer sandwich plate theory for minimizing weight, deflection, and buckling load. The method used a MATLAB-based model, governed by Hamilton's principle, and GA-based optimization method to find the Pareto front. The method was validated based on the First Order Shear Deformation Theory. Feng [206] studied a novel optimization framework for a sandwich structure made of freeform facesheets and an intricate porous Triply Periodic Minimal Surfaces (TPMS) core. The model was based on the Constrained Improved Particle Swarm Optimization algorithm to maximize mechanical indexes (surface area and density-based parameters). The method was validated by a 3D-printed scale-down wing structure using the TPMS core.

Fan [207] optimized the stacking sequences of CFRP facesheets of a multi-sandwich structure made of a ROHACELL foam core, using a Multi-chromosomal GA. The method was used to minimize structural weight while considering strength and buckling as design constraints. The analytical model used the Hashin criterion and the maximum stress criterion to predict the failure under various loading conditions. The method was validated through experimental testing. Montemurro [208] presented a multi-scale (at meso- and macro-scales) optimization strategy for simultaneous shape and material optimization of a

sandwich construction made of CFRP facesheets and a metallic cellular core. The model used a GA and Non-Uniform Rational B-Splines (NURBS)-based shape representation to minimize weight under manufacturability, buckling, and stiffness constraints. The model was implemented using MATLAB (for NURBS geometry) and GAs, coupled with ANSYS FE simulations. At the meso level, the Representative Volume Element of the periodic cellular core, and at the macro level, panel buckling analysis, was used. The model was validated with 3D-printed samples. Gholami [209] optimized a composite sandwich panel made of a polycarbonate honeycomb core, subjected to a uniformly distributed normal load, using Niching Memetic PSO and Locally Informed PSO to minimize weight. The model used the analytical Navier-type solution and closed-form expressions to calculate macroscopic in-plane elastic constants of the honeycomb, which were used to predict the maximum deflection of the investigated panel. Ilyani Akmar [210] proposed a multi-objective optimization model for sandwich structures by using Elitist Non-Dominated Sorting Evolution Strategy, integrating Evolution Strategies into NSGA-II to minimize deflection, weight, and cost in terms of the Pareto front. An analytical model was used to compute strength parameters and validated through a simply supported cantilever sandwich beam.

Yang [211] proposed a novel data-driven Improved Artificial Electric Field Algorithm with an ANN model for optimizing the anti-blast performance of multi-core auxetic concave arc-type honeycomb cell core sandwich blast walls. The model used LSDYNA FEA-generated data with LH sampling. The model performance was verified with test results of nine different ANN models. Bohara [212] studied a novel large-scale auxetic hourglass structure for protective applications using a multi-objective optimization model combining a Radial Basis Function (RBF) Neural Network and NSGA-II algorithm to maximize SEA. A numerical model using LS-DYNA under quasi-static and blast loadings was used to generate the response dataset for the surrogate model with the RBF. The NSGA-II was used to get the Pareto front, and the optimal structure was achieved through the Ideal Point Method. The method was validated with 3D-printed sample testing. Santosa [213] presented a multi-objective optimization method for four types of auxetic sandwich panels made of re-entrant honeycomb, double-arrow honeycomb, star honeycomb, and tetra-chiral honeycomb for the blast resistance of armored vehicles to maximize SEA and minimize permanent deformation. The optimization model used FE simulations, the NSGA-II algorithm, the ANN metamodel, CONWEP, and the SHAP method for global sensitivity analysis to get the Pareto front.

Mallick [214] proposed a novel Multi-Objective Genetic Algorithm for optimizing a sandwich structure using various types of Al honeycomb cores. The method used NSGA to maximize SEA and minimize weight, while the transmitted force and the displacement were used as design constraints. The elaborated method used a Python script to integrate MATLAB and ABAQUS FE solver using parallel computing to generate response surface. For visualizing the post optimization results, ANOVA regression plots were used. Kamarian [215] studied the optimization of 3D-printed sandwich beams using PLA-based chiral-core under compressive loads to maximize the SEA. The model used the Response Surface Method and the ML-based Deep Neural Network, trained with the Bayesian and Conjugate Gradient algorithms and experimental data. The study utilized design optimization through Design Expert v23.1 Software and was validated through a statistical analysis scheme, ANOVA, by calculating p-values.

Sun [216] optimized the convective cooling efficiency of a sandwich structure made of a hierarchical Al-based corrugated core. The method used an Artificial Intelligence-based Ant Colony Optimization Algorithm to maximize heat transfer efficiency. A theoretical model was built upon the classical fin approach, coupling wall heat conduction and fluid

convection in the core for all phases of fluid flow (laminar, transition, and turbulent). The model was validated through numerical simulations. Peng [217] presented a multi-objective optimization method for a sandwich structure made of a pyramid lattice core to optimize heat transfer through ANSYS Fluent Computational Fluid Dynamics with the k-ω SST turbulence model. Collapse strength analysis SIMPLE algorithm was used, which couples pressure and velocity. The scheme was implemented in MATLAB using the Response Surface Method for Design of Experiments model. The NSGA-II algorithm was used to identify the Pareto front. Furthermore, the performance was evaluated using the ANOVA method. The model was validated experimentally using 3D-printed samples under forced convection heat transfer load and quasi-static out-of-plane compression tests.

Feng [218] proposed a Multi-Objective Genetic Algorithm for optimizing a sandwich construction made of an Al honeycomb core to minimize mass by taking into consideration natural frequency and stiffness design constraints. The approach used the Equivalent Plate Theory and a decoupling strategy for complex systems, providing global optimal solutions in terms of the Pareto front for a single cell frame structure. Du [219] elaborated a single- and multi-objective optimization method for a sandwich panel made of FRP facesheets and a double-curved magneto-rheological fluid core using the Bee Optimization Algorithm to maximize the first modal loss factor and minimize mass. The model used the Improved High Order Theory, extended Hamilton's principle, FSDT, and TOPSIS to extract motion equations for Pareto fronts. Xu [220] elaborated a multi-objective optimization method for an automotive roof sandwich panel to minimize mass and maximize transmission loss using the NSGA-II algorithm to get the Pareto front. The model was implemented using MATLAB for the analytical formulation of structural and acoustic models. The method was validated through experimental testing of samples with an Al foam core, honeycomb core, and a combination of both.

10. Conclusions

There is an increasing demand for lightweight, high-performance, cost-effective, and sustainable structures in practical applications. These requirements can be fulfilled by the use of optimal composite sandwich constructions.

This review study covers the most relevant articles on the topic of optimization of composite sandwich structures published in the last decade. An extensive analysis of recent advancements in optimization techniques was carried out.

The main focus of the study is on the type of sandwich structures, core and facesheet materials, elaborated optimization procedures, loading and boundary conditions, analytical and numerical simulation procedures, and tools, as well as the experimental and numerical validation of the proposed optimization procedures. The research studies on single- and multi-objective optimization of composite sandwich structures reviewed in this article are categorized as analytical and numerical design procedures, novel core materials and structural design methodologies, topology optimization procedures, structural optimization under various loading and boundary conditions, performance-based optimization studies, and their applications. The article also discusses the Machine Learning-based Genetic Algorithms applied for the optimization of sandwich constructions.

Based on the synthesis of the reviewed articles, the main scientific contributions of the review article are the following:

1. A typical optimization problem includes the objective functions, design variables, and design constraints. An optimization procedure consists of an analytical or FE-based numerical simulation method. Depending on the complexity of the optimization problem, an adequate optimization algorithm has to be used to find the optimal variables. Finally, experimental or simulation-based validation has to be completed.

2. The performance of composite sandwich structures depends mainly on the material, type, and geometry of the core and the facesheet structural components. These characteristics are the main parameters to be optimized.
   The most frequently applied design variables of the cores in the case of optimization of sandwich structures are their material, geometry, height, wall thickness, etc. There are several core geometries used in optimization studies, like the lattice core, auxetic core, functionally graded core, corrugated core, honeycomb core, metallic or polymer foam core, and bio-inspired core.
   The most commonly used design variables of the facesheets in the case of optimization of sandwich structures are their thickness, fiber orientation, layer sequence, as well as materials like carbon fiber, glass fiber, Kevlar fiber, or metallic materials, i.e., aluminum or steel.
3. Based on the analysis of the reviewed articles, it can be concluded that the main optimization fields of sandwich structures are optimization of the core and the facesheet structural elements, as well as optimization of the whole sandwich construction.
   Most of the studies focus on the topological optimization of cores, which emphasizes how different core configurations influence the performance of sandwich constructions. Several optimization procedures use ML-based topological optimization tools (e.g., nTop Simulation module, Altair's OptiStruct 2017 software, etc.) along with material models like the SIMP method to achieve the optimal core configuration under various loading conditions. With the advancement in 3D-printing technology, the possibility of validating complex-shaped lattice core structures is also a frequently researched topic. The most important parameters to be optimized for facesheets of sandwich constructions are their material, laminate thickness, fiber orientation, and stacking sequence.
   Most of the performance-based optimization studies include methods to improve the acoustic performance of the whole sandwich constructions, to achieve the optimal parameters like sound transmission loss, sound absorption coefficient, and structural weight.
4. Several optimization methods are proposed for the composite sandwich constructions based on the aimed objective function/functions, as well as taking into consideration the required design constraints.
   The most commonly used objective functions during the structural optimization are the structural weight, cost, specific energy absorption, transmitted load, and sound transmission loss.
   The most frequently used design constraints are structural deformations, bending and torsional stiffness, eigenfrequency, facesheet and core buckling load, and stress. Furthermore, several loading conditions are used in the structural optimization of sandwich constructions, i.e., compressive or buckling load, bending load, axial load, hydrostatic load, impact load, blast load, thermal load, and dynamic or vibration load.
5. An efficient optimization procedure can significantly reduce the computational time; however, the reliability and the precision of the optimization results are also significant. To achieve this, Machine Learning (ML) techniques such as Artificial Neural Networks (ANNs) are used with Stochastic methods like Genetic Algorithms (GAs) and Particle Swarm Optimization (PSO) algorithms. The most preferred ML-based algorithm applied in the case of single- and multi-objective optimization is the Non-dominating Sorting Genetic Algorithm-II (NSGA-II). Additionally, other optimization methods, including Generalized Regression Neural Networks (GRNN), the Extreme Learning Machine (ELM), Support Vector Regression (SVR), and Radial Basis Functions (RBFs), are also commonly used. Other frequently used general optimization methods are the Method of Feasible Directions (MFD), Flexible Tolerance Optimiza-

tion (FTO), Multi-Island Genetic Algorithm (MIGA), Multi-Objective Particle Swarm Optimization (MOPSO), and the Bidirectional Evolutionary Structural Optimization (BESO) algorithm.

6. Finite Element Methods are generally used for numerical simulations during the optimization of sandwich constructions for the validation of optimal results. Furthermore, analytical/mathematical techniques and numerical simulations are used to construct surrogate models by using further methods such as the Response Surface Method (RSM) and Latin Hypercube Sampling Method (LHS). The most commonly applied analytical methods for the simulation models are the First Order Shear Deformation Theories (FOSDTs), the Higher Order Shear Deformation Theories (HOSDTs), and the Rayleigh–Ritz method. The most frequently used failure theory in the numerical simulations is the Classical Laminate Plate Theory (CLPT).
7. Various Finite Element simulation tools—including ANSYS, Nastran, ABAQUS CAE, and LS-DYNA—are widely used during the optimization of composite sandwich structures. These software packages enable the development of detailed FE models of complete sandwich constructions or novel core designs (e.g., lattice core or bio-inspired core structures). The FE-based numerical simulations have dual purposes: validating optimization results and experimental findings, while also being integrated within optimization loops to perform structural analyses of various design variables generated by optimization algorithms.
   Meanwhile, MATLAB's Optimization Toolbox offers built-in algorithms like Genetic Algorithms, which have been widely adopted in optimization studies. Additionally, new optimization frameworks are developed using MATLAB and Python scripting, which are integrated with FE simulations for comprehensive structural analysis.
8. Experimental validation studies were systematically conducted to verify optimization results for sandwich structures. Test specimens were manufactured either in compliance with relevant ASTM standards (e.g., ASTM D7249 for facesheet strength and stiffness properties) or using systematically varied material combinations and geometric configurations of facesheets and cores. The experimentation included comprehensive mechanical and functional testing: three-point bending tests to evaluate flexural properties, buckling load tests for stability assessment, dynamic analyses (vibration and modal frequency characterization), impact resistance evaluations, as well as thermal insulation and acoustic performance measurements. Relating to the core-specific validation, most of the studies used 3D-printed core specimens subjected to multiple loading conditions. These experimental investigations provided critical verification of numerical simulation results while assessing structural performance under realistic operating conditions.

Based on a deep review of current optimization research in the field of sandwich structures, the following future research directions can be identified:

1. Global sustainability demands for future composite structures require the use of eco-friendly bio-composites in the core and facesheets of composite sandwich constructions. However, these bio-composites have inherent variability in properties, which makes the design of the composite sandwich structure challenging. This necessitates the application of advanced optimization techniques, taking into consideration the huge variety of composite material characteristics while maintaining structural integrity with a lightweight performance. Moreover, hybrid composite materials, i.e., combinations of synthetic and bio-composites, can be utilized for facesheets and the core of sandwich constructions for structural optimization in various applications.
2. Efficient structural design of the core element is critical for enhancing the performance of sandwich constructions. Recent advances in 3D-printing technologies enable the

manufacturing of complex core constructions (e.g., lattice and bio-inspired cores). Topology optimization methods can be applied to refine core designs, which significantly improves the overall structural efficiency of sandwich constructions under various loading conditions.
Furthermore, novel optimization procedures for core structural design and material selection should be developed in order to minimize the manufacturing time and material utilization, resulting in an overall reduction in structural cost.

3. The optimization of sandwich structures has become increasingly complex, which considers multiple competing objectives simultaneously. Modern optimization problems involve complex objective functions that balance structural weight, material costs, manufacturing time, and performance requirements. These also have to account for challenging combined loading conditions like thermal-mechanical stresses and dynamic impacts, along with manufacturing constraints from processes like 3D printing. Additionally, several design constraints and design variables further complicate the optimization processes. To effectively address these complex challenges, novel multi-objective optimization methods have to be developed. These advanced methods can simultaneously optimize all competing objectives, such as minimizing weight and costs while maximizing structural performance for given practical applications.
4. Future optimization methods have to integrate modern Machine Learning techniques with advanced computational approaches to address the challenges in solving the complex optimization problems of sandwich structures. Hybrid optimization frameworks can combine established algorithms like Genetic Algorithms and Particle Swarm Optimization with ML techniques such as Artificial Neural Networks. These optimization methodologies can use the FE-based high-fidelity simulation data to train the ANNs for developing accurate surrogate models, which will reduce the computation time for the optimization process while maintaining the accuracy of results.

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Abbreviations

The following abbreviations are used in this manuscript:

Al	Aluminum
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
BESO	Bidirectional Evolutionary Structural Optimization
BPNN	Back Propagation Neural Network
CDM	Continuum Damage Mechanics
CFE	Crushing Force Efficiency
CFRP	Carbon Fiber-Reinforced Plastic
CLPT	Classical Laminate Plate Theory
CZM	Cohesive Zone Model
DNN	Deep Neural Network
DOE	Design of Experiment

ELM	Extreme Learning Machine
FE	Finite Element
FGM	Functionally Graded Material
FOSDT	First Order Shear Deformation Theory
FRP	Fiber-Reinforced Polymers
FTO	Flexible Tolerance Optimization
GA	Genetic Algorithm
GFRP	Glass Fiber-Reinforced Polymer
GRNN	Generalized Regression Neural Network
HOSDT	Higher Order Shear Deformation Theory
LHS	Latin Hypercube Sampling
LM	Levenberg Marquardt
MAE	Mean Absolute Error
MDPI	Multidisciplinary Digital Publishing Institute
MFD	Method of Feasible Directions
MIGA	Multi-Island Genetic Algorithm
ML	Machine Learning
MOGA	Multi-Objective Genetic Algorithm
MOPSO	Multi-Objective Particle Swarm Optimization
MSE	Mean Squared Error
NASA	National Aeronautics and Space Administration
NDI	Non-Destructive Inspection
NN	Neural Network
NSGA	Non-Dominated Sorting Genetic Algorithm
NURBS	Non-Uniform Rational B-Splines
OSP	Occupant Side Plate
PLA	Poly Lactic Acid
PR	Polynomial Regression
PSO	Particle Swarm Optimization
RAMP	Rational Approximation of Material Properties
RBF	Radial Basis Functions
RMSE	Root Mean Squared Error
RSM	Response Surface Method
SAC	Sound Absorption Coefficient
SEA	Specific Energy Absorption
SHM	Structural Health Monitoring
SIMP	Solid Isotropic Microstructure with Penalization
SSP	Struck Side Plate
STL	Sound Transmission Loss
SVR	Support Vector Regression
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TPMS	Triply Periodic Minimal Surfaces

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