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Review

Advanced Composite Materials for Structure Strengthening and Resilience Improvement

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Abstract: Advanced composite materials have excellent performance and broad engineering application prospects, and have received widespread attention in recent years. Advanced composite materials can mainly be divided into fiber-reinforced composite materials, laminated composite materials, matrix composite materials, and other composite materials. This article provides a comprehensive overview of the types and characteristics of advanced composite materials, and provides a comprehensive evaluation of the latest research on structural strengthening and resilience improvement in advanced composite materials from the perspectives of new methods, modeling optimization, and practical applications. In the field of fiber-reinforced composite materials, the hybrid technology of carbon fiber and glass fiber can achieve dual advantages in combining the two materials. The maximum increase in mechanical properties of multilayer sandwich RH plate by hybrid technology is 435.4% (tensile strength), 149.2% (flexural strength), and 110.7~114.2% (shear strength), respectively. In the field of laminated composite materials, different mechanical properties of laminated composite materials can be obtained by changing the deposition sequence. In the field of matrix composites, nano copper oxide particles prepared by nanotechnology can increase the hardness and tensile strength of the metal matrix material by 77% and 78%, respectively. In the field of other composite materials, viscoelastic materials and magnetorheological variants have received widespread attention. The development of composite materials benefits from the promotion of new methods and technologies, but there are still problems such as complex preparation, high cost, and unstable performance. Considering the characteristics, application requirements, cost, complexity, and performance of different types of composite materials, further improvements and innovations are needed in modeling and optimization to better meet practical engineering needs, such as the application of advanced composite materials in civil engineering, ships, automobiles, batteries, and other fields.

Keywords: advanced composite materials; structure strengthening; resilience improvement; fiber-reinforced composite materials; laminated composite materials; matrix composite materials

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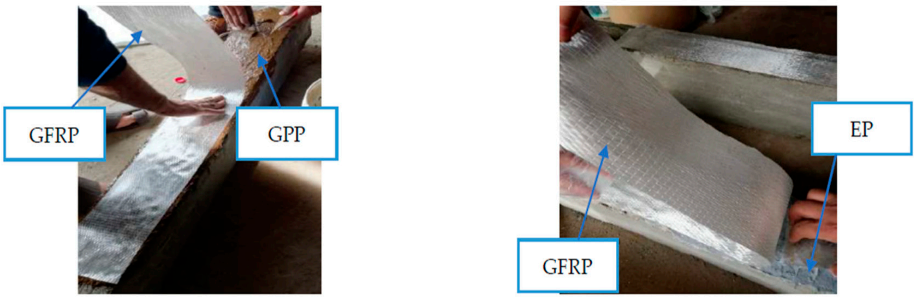
1. Introduction

With the development of science and technology and the diversification of social needs, industrial development has increasingly higher requirements for material properties. Many types of materials have received widespread attention in this field, from commonly used composite materials (such as glass fibers) to advanced composite materials (such as carbon fibers, magnetorheological elastomers, metal substrates, etc.). Advanced composite materials have excellent performance and broad engineering application prospects, and have received widespread attention in recent years. Therefore, increasingly more scholars are beginning to study structural strengthening and resilience improvement in advanced composite materials, which is crucial for improving the safety, reliability, and durability of composite equipment. Advanced composite materials can be mainly divided into four categories: fiber-reinforced composite materials, laminated composite materials, matrix composite materials, and other composite materials. The distinction among these four material categories can be outlined in the following manner: Firstly, fiber-reinforced composite materials are mainly characterized by embedding high-strength fiber materials as reinforcing materials in a continuous matrix. Fibers can be carbon fiber, glass fiber, aramid fiber, etc. Usually, fibers in fiber-reinforced composite materials are distributed in a continuous form in the matrix to provide reinforcement effects. Secondly, from a precise perspective, laminated composite materials are also categorized within the realm of fiber-reinforced composite materials. However, unlike traditional fiber-reinforced composite materials, they are alternately stacked with fiber layers, each with a different fiber direction, and then formed by pressing layer by layer. The arrangement of these laminated fibers in different directions provides excellent anisotropic properties, allowing the material to exhibit excellent mechanical properties in multiple directions. Thirdly, matrix composite materials refer to composite materials formed by the combination of two or more different materials, with at least one material serving as the matrix and the other materials serving as reinforcing or filling materials. The matrix material is usually metal or ceramic, while the reinforcing material can be fiber, particle, or sheet-like material. Lastly, other composite materials do not belong to any of these types, including composite materials with special applications in certain fields such as viscoelastic materials, magnetorheological fluids, cement mortar, etc. The continuous research and improvement in the performance of these four types of advanced composite materials from different research perspectives is still of great significance. This article provides a summary of new methods, modeling and simulation, and new applications for enhancing the structure and resilience of advanced composite materials. The intention is to offer the most recent research advancements in advanced composite materials, potentially benefiting other researchers in acquiring ideas and enhancing their research endeavors.

2. State-of-Art Concerning Fiber-Reinforced Composite Materials in Structural Reinforcement and Resilience Enhancement

2.1. Comparison of Common Fiber-Reinforced Composite Materials and Their Mixing Techniques

One of the biggest problems facing contemporary civil engineering is the strengthening, updating, and transformation of old structures. One of the most promising answers to these needs is the use of fiber-reinforced polymer (FRP). FRP is a composite material composed of synthetic fibers (such as carbon, glass, asbestos, beryllium, molybdenum, and aromatic polyamides) and synthetic polymer matrices (such as epoxy resin, polyester, and vinyl ester) [1]. Glass fiber-reinforced polymer (GFRP) and carbon fiber-reinforced polymer (CFRP) are the most suitable reinforcement materials for various civil engineering applications, as they have the highest temperature resistance, greatest strength, and lowest cost [2]. Bonding carbon fiber-reinforced polymer (CFRP) to the tensile surface of components can significantly improve structural strength. In addition, the type of adhesive material used is important to prevent debonding of the CFRP. Rageh has proposed two unique methods to enhance the adhesion between glass fiber-reinforced polymer (GFRP) and RC concrete surfaces, as shown in Figure 1 [3]. The purpose of Figure 1 is to demonstrate how CFRP is bonded to RC concrete beams through two different bonding materials, EP and GPP. The two adhesive materials are epoxy (EP) and geopolymer (GPP) with different proportions of short glass fiber (SGF). A more conventional method than the two proposed unique methods is to use epoxy resin to bond structural elements to steel plates. Through experiments and ABAQUS simulations, it has been proven that geopolymer slurries with and without short glass fibers in reinforced beams outperform epoxy resins in terms of performance and cost. At the same time, increasing the SGF ratio in GPP has a significant effect on improving the bearing capacity of the beam. GPP as an adhesive material enhances the maximum beam deflection and the beam ductility factor better than EP. At present, CFRP and GFRP composite materials have been applied in fields such as bridge reinforcement and building components due to their excellent performance, as is shown in Table 1. In recent years, the hybrid technology of carbon fiber and glass fiber can achieve the dual advantages of combining the two materials. Xian designed two types of carbon fiber/glass fiber hybrid rods with sandwich structures through pultrusion technology: fiber random hybrid (RH) with multilayer sandwich structures and fiber core–shell hybrid (CH) with single-layer sandwich structures [4]. The experimental results show that the tensile strength, flexural strength, and in-plane shear strength of the multilayer sandwich RH plate are increased by 50%, 30–40%, and 18%, respectively. With the increase in bending load, the flexural strength and in-plane shear strength decreased by 18% and 19%, respectively. By evenly dispersing carbon fibers into glass fibers, the problem of uneven interfacial stress concentration in multilayer sandwich RH panels can be effectively alleviated. The interfacial shear strength is more sensitive to bending load and immersion temperature. The long-term life prediction results show that the maximum increase in mechanical properties of multilayer sandwich RH plates is 435.4% (tensile strength), 149.2% (flexural strength), and 110.7~114.2% (shear strength). The mixing technology of basalt fiber and glass aramid fiber can also improve the mechanical properties of composite materials. Mazur used aramid fiber (AF) and basalt fiber (BF) as reinforcement materials and prepared polylactic acid composite materials through injection molding [5]. The increase in fiber content significantly improved the mechanical properties. AF increased Young's modulus and the tensile strength of the composite material, while BF increased the tensile strength. The trend in thermodynamic testing is similar to that for mechanical testing, where the higher the filler content, the higher the storage modulus. At the same time, adding AF and BF can increase the stiffness of the composite material, with the same effect as adding expensive aramid fibers of the same weight. The addition of fiber did not change the characteristic temperature obtained by differential scanning calorimetry. This work provides the possibility for creating hybrid materials with customizable mechanical and structural properties, and the use of different fibers can adjust the performance of composite materials to make them suitable for specific applications.



(a) (b)

Figure 1. Strengthening RC beams with (**a**) GFRP and (**b**) EP (adapted from [3]).

Table 1. Performance comparison between CFRP and GFRP.

Performance	CFRP	GFRP
mechanical properties	high strength and stiffness	good flexibility and impact toughness
fatigue performance	higher fatigue strength	poor fatigue performance
creep	good stability at high temperatures	poor stability at high temperatures
durability	good durability	relatively poor CFRP
cost	expensive	less expensive

However, research has shown that there are various types of FRP debonding failures regardless the type of bonding material or bonding method used, including middle crack debonding, concrete cover separation, and plate end debonding. When FRP degumming fails, the effectiveness of the strengthening mechanism is greatly reduced [6–8]. A solution to this problem may be to combine effective installation procedures with well-defined and controlled prestressing of CFRP materials. An anchor system is one of the commonly used installation procedures and strengthening technologies in construction engineering, which has a wide range of applications in strengthening and reinforcing concrete structures, steel structures, and other components. When FRP debonding fails, this anchoring system may significantly improve the debonding process and interface bonding between FRP and RC concrete surfaces [9,10]. Schmidt studied a new type of prestressed CFRP NSMR reinforcement anchorage system, as shown in Figure 2 [11]. The purpose of Figure 2 is to show the approximate appearance of the anchoring system. The system has undergone five laboratory tests and has been successfully used in pilot projects to reinforce cast-in-place concrete bridges. The study focuses on considering the system's responsiveness to ensure that it can provide consistent load/deformation curves, yield thresholds, and yield mechanisms. All reinforcement systems have undergone in situ anticounterfeiting loading after installation and prestressing procedures have been carried out as required to eliminate any possible failure modes below the anticounterfeiting loading level, as is shown in Figure 3. This study indicates that this new anchoring system has performed well in laboratory testing and pilot projects, and has great potential for application. The fatigue resistance of CFRP and GFRP materials is an important mechanical property. Engineering structures are often affected by cyclic loads, which can lead to material fatigue and adversely affect the service life and damage tolerance of components and connections. Alam detailed the effect of cyclic loading on the fatigue performance of carbon fiber composite materials [12]. This article argues that more targeted research is needed on how the manufacturing of CFRP, inherent material defects, crosslinking density (curing), and material uniformity will affect the dispersion degree of CFRP under cyclic loading. Wu verified their good fatigue resistance by studying the fatigue performance and macroscopic damage in CFRP bending anchor cables [13]. Under stress amplitudes of 500 and 600 MPa, the residual strength retention rates of CFRP rods after two million fatigue cycles are as high as 95.1% and 76.7%. The bending–anchoring CFRP anchor cable can withstand two million fatigue loads with a maximum stress of 0.4 σ Ult, with an amplitude of 500 MPa and without significant fatigue damage. Under more severe fatigue loading conditions, the macroscopic damage of CFRP bars mainly manifests as fiber splitting and compression shear fracture. The additional shear effect is a decisive factor affecting the fatigue resistance of CFRP rods. These research results contribute to optimizing the bending anchorage system, improving its fatigue resistance, and promoting the application and development of CFRP cables and bending anchorage systems in bridge structures.

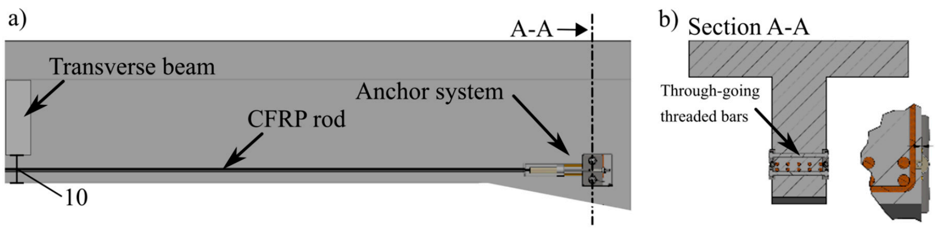


Figure 2. Side view (**a**) and section view (**b**) of the proposed strengthening method (adapted from [11]).

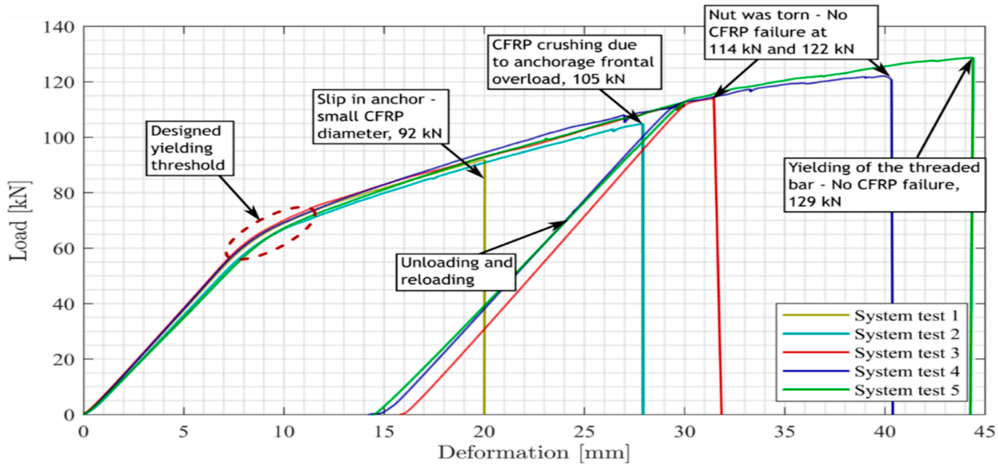


Figure 3. Load deformation test curves (adapted from [11]).

2.2. Methods for Improving the Performance of Fiber-Reinforced Composite Materials

Fiber-reinforced composite materials, as an important structural material, are influenced by various factors in their performance. In order to improve the performance of fiber-reinforced composite materials, many new improvement methods have emerged in recent years, such as surface modification, crosslinking, changing fiber orientation, additives, etc. Yang studied the analysis method of fiber fracture and orientation changes during the manufacturing process of short-fiber-reinforced composite materials [14]. Using a simplified CFD model to study experimental phenomena, the results showed that nozzle diameter has a significant impact on fiber fracture and mechanical properties, with smaller nozzle diameters leading to higher shear rates and more fiber fracture. Fibers of different lengths have different fracture ratios at different printing stages. The direction of the fibers inside the bead is related to the height of the layer. A larger layer height leads to better alignment, but it will reduce mechanical performance. Song adopted a new fiber surface treatment method to improve interface compatibility, and the treated fibers are shown in Figure 4. The use of a low-cost alkyl ketene dimer (AKD) is aimed at replacing relatively expensive silane-based reagents. The effect of fiber surface treatment on the interfacial compatibility and mechanical properties of composite materials was studied [15]. Lu proposed a fiber modification method by forming a thin SiO_2 layer on the surface of carbon fibers and reacting with $Ca(OH)_2$ to form calcium silicate hydrates, resulting in condensation at the fiber matrix interface [16]. The experiment found that the bending strength and tensile strength of carbon fiber-reinforced cement-based composites modified with nano SiO_2 were increased by 24.7% and 25.1%, respectively. At the same time, nanomodification enhances the compactness of the interface transition zone, reduces porosity, and increases the post crack behavior and resilience performance of the material. The research results indicate that this fiber modification method can effectively improve the performance of fiber-reinforced cement-based composites.

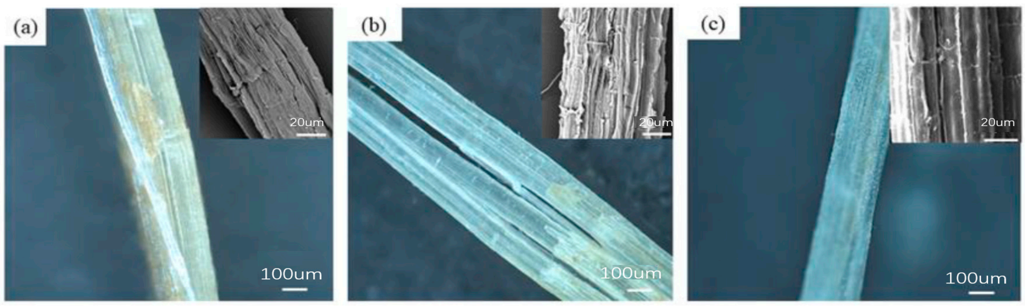


Figure 4. Micromorphology and structure of fibers with different treatments (**a**) H, (**b**) HP, and (**c**) HPM (adapted from [15]).

Lee investigated how fiber orientation and distribution influenced the mechanical behavior of short-fiber-reinforced thermoplastic composites by using synchrotron X-ray imaging combined with in situ tensile testing and digital volume correlation analysis [17]. This research found that fiber orientation is crucial for local compressive strain and anisotropic mechanical behavior, while load-direction strain is greatly affected by local volume fraction. The local volume fraction also determines the stiffness of the subvolumes that can be estimated from the analysis homogenization model. Batu studied the effects of different fiber volume fractions and fiber orientations on the mechanical properties of fake banana/glass fiber-reinforced hybrid composites [18]. The composites were manufactured by hand-lay technology, and the tensile, flexural, and compressive properties were measured by ASTM standard test methods. The effects of volume fraction and fiber orientation on the properties of composite materials were analyzed, and the results showed that both significantly affect the mechanical properties of hybrid composite materials. Zhang prepared five types of paper based composite friction materials with different glass fiber contents through the papermaking process, and studied the effect of glass fiber on material properties [19]. The results indicate that the sample with 10 wt.% glass fiber has the best mechanical properties and wear resistance. With the increase in glass fiber content, the shear strength first increases and then decreases, the compressibility increases, and the recovery rate decreases. Additionally, the friction coefficient first increases and then decreases with the increase in glass fiber content, and the optimal composition effect is for samples with medium glass fiber content. Liu was able to improve the strength of SFRTPCs by adding a small amount of strong materials to the matrix to connect short fibers [20]. In this work, micromechanical analysis was conducted using a finite element model, taking into account the fiber crosslinking effect. The simulation results showed that increasing the mass fraction of the bonding material can improve the mechanical properties of short-fiber-reinforced thermoplastic composites (SFRTPCs); by increasing the strength of the connecting rod material, the tensile strength and resilience of the composite material were especially improved. Shivamurthy studied the possibility of producing jute fiber-reinforced epoxy composites using a mixture of alkaline fibers and cashew shell liquid epoxy resin, and tested the mechanical properties [21]. The results show that the JFRE composite material made from modified matrix and alkaline-treated jute fibers has an average tensile strength of 679 MPa and a bending strength of 88.83 MPa, exhibiting better mechanical properties and can be used for high-strength applications. The emergence of these methods has greatly promoted the development of fiber-reinforced composite materials. However, there are still problems and defects in fiber-reinforced composite materials, such as complex preparation processes, high costs, and poor performance stability, which need to be addressed through technological innovation.

2.3. Model Algorithm for Optimizing Fiber-Reinforced Composite Materials

Establishing model optimization algorithms plays an important role in the development of fiber-reinforced composite materials. At present, the commonly used modeling methods include multiscale topology optimization, theoretical model, and so on. Optimization algorithms mainly include genetic algorithms, trial-and-error methods, etc. The application of these models and algorithms can better predict the mechanical properties of composite materials, thereby optimizing the ratio and preparation process of composite materials. Alhaddad uses artificial neural network modeling methods to predict the performance of composite materials, especially the ultimate tensile strength [22]. At the same time, the artificial bee colony algorithm is used to optimize printing and material parameters to achieve maximum tensile strength. The research results indicate that fiber properties, fiber morphology, fiber orientation, and fiber volume fraction have the greatest impact on the tensile strength of composite materials. Duan introduced a novel multiscale and multimaterial anisotropic penalty (MMCAP) model [23]. This model is tailored for exploring the design optimization of composite structures with variable stiffness (VS), reinforced with fibers. The objective is to minimize structural compliance, as demonstrated in Figure 5. This model utilizes improved solid isotropic material punishment (SIMP) and discrete material optimization (DMO) at the macro- and microscales, respectively, to achieve clear macromultimaterial structure topology and microspecific discrete fiber-laying angle selection. This method can effectively achieve multimaterial and multiscale design optimization of fiber-reinforced composite structures, achieving clear macroscopic topology of multimaterial structures and microscopic fiber-laying angles. This provides a new implementation strategy for lightweight, multimaterial, and multiscale design optimization of composite materials. Obid has proposed a new constitutive model that can describe the tensile and compressive responses of nonlinear anisotropic fiber materials under general stress states [24]. Built upon the Ramberg–Osgood model, this framework is expanded by incorporating triaxial stress invariance as a marker for stress-state classification. This extension aims to account for tension–compression asymmetry within multiaxial stress conditions. Compared to other models, this model provides an elegant formula for describing all phenomena and implements a simple calibration program. Therefore, this method can describe the nonlinear behavior and tension compression asymmetry of fiber-reinforced composite materials, and has better advantages. Liu studied the fracture behavior of fiber-reinforced composite laminates under shear dominant loads through experiments and numerical simulations [25]. The V-notch guide-rail shear testing method was used, and the fracture surface was studied using scanning electron microscopy. At the same time, a high-fidelity, elastic–plastic damage model was developed to predict shear fracture behavior. The experimental results show that the composite sample undergoes a significant nonlinear process and exhibits a series of failure modes. The simulation results exhibit good correlation with the experimental results, demonstrating the predictive capability of the developed model. This study is of great significance for the design of composite material structures. Sakata utilized SEM images of randomly arranged, unidirectional fiber-reinforced composite samples [26]. The apparent strength in each segment was extracted, and the validity of the random field modeling for local strength was examined. Through microstructure simulation, the spatially varying random apparent fracture strength was subsequently calculated. Single scale and multiscale analysis were attempted in this study, and random field and its autocorrelation function were calculated by using the moving window method. The numerical results indicate that a smaller window is preferred for a more accurate evaluation of apparent strength. From the perspective of establishing models and optimizing algorithms, there are still some shortcomings in the development of fiber-reinforced composite materials, such as the lack of effective prediction models and immature optimization algorithms.

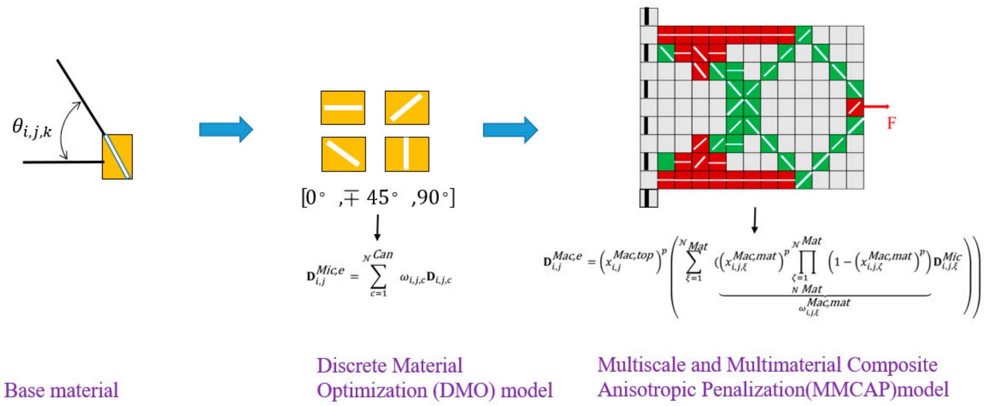


Figure 5. Schematic showing concurrent macroscale and multimaterial topology design optimization for composite laminates with minimum structural compliance.

2.4. Application of Fiber-Reinforced Composite Materials in Practical Projects

However, whether it is new technological methods or innovative modeling and simulation methods, their core goal is to improve practical applications. The mixed fiber technology in technical methods can significantly improve the strength and stiffness of materials, thereby producing lighter and higher strength materials for practical engineering, such as civil infrastructure reinforcement. The proposal for novel modeling and simulation methods, such as the MMCAP model, provides a new solution for lightweight application and multiscale optimization application of composite materials. Fiber-reinforced composite materials have been widely used in practical engineering and projects, mainly in fields such as aerospace, automotive, shipbuilding, architecture, electronics, etc. Lv used ultrasonic-assisted electroplating technology to evenly coat copper coatings on the surface of carbon fibers to improve their wettability with the aluminum substrate [27]. This research found a linear relationship between the thickness of copper coatings and electroplating time. At the same time, copper coating can promote the infiltration of aluminum melt into carbon fiber bundles, thereby enhancing the mechanical properties of composite materials. The optimal coating thickness is 1.5 microns, and the tensile strength of the composite material is 169 MPa, the elastic modulus is 80 GPa, and the elongation is 4.2%. Therefore, ultrasonic-assisted electroplating technology can improve the performance of carbon fiber-reinforced aluminum matrix composites and enhance their application prospects in industrial and commercial applications. Kumar explored the preparation of carbon fiber powder-reinforced polymer composites and their application in pump impellers [28]. Researchers use specific materials and molds to predict the strength of composite materials through tensile, bending, and impact testing, and use nondestructive testing methods to predict crack formation. The results showed that the strength of composite materials was superior to that of metals, cast iron, and structural steel, and ultimately achieved application in pump impellers. Researchers believe that by changing the thickness and combination of fibers, higher strength and corrosion resistance can still be achieved compared to lightweight materials such as steel and cast iron. In the future, this method can be applied to the field of pump impellers. Jeong investigated the assessment of mechanical performance for cargo sealing systems on liquid natural gas transport vessels [29]. This was accomplished by employing the continuous installation of E-glass fiber-reinforced composite materials with extended structures, as depicted in Figure 6. This research revealed that the material properties associated with this specific length can effectively act as representative material properties for infinite lengths, offering a dependable characterization of the material attributes pertaining to extended structures of infinite nature. By using a Weibull distribution to calculate the failure strength, the study also found that the standard deviation and failure strength of the material increase with the increase in length within a specific length. These findings are of great significance for ensuring the safety of liquid natural gas transport ships.

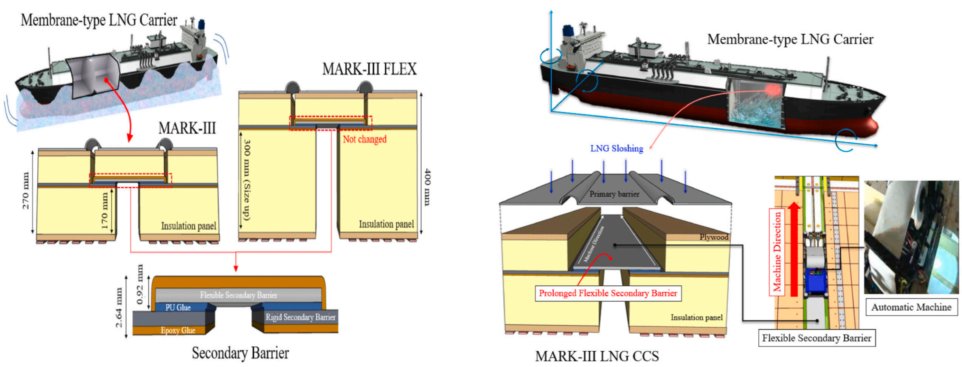


Figure 6. Schematic of the secondary barrier in the MARK-III and FLEX LNG CCS (adapted from [29]).

Saintane prepared two composite samples using carbon-based materials and powder metallurgy methods to manufacture carbon fiber-reinforced polymer composites to improve friction performance [30]. By conducting shore hardness testing and compression testing on the sample, it was proven that Sample 2 had higher hardness and compression strength. The results of this study indicate that the carbon-based polymer friction composite material manufactured has excellent mechanical properties and can be used as a candidate material for commercial brake pads and other application fields. Additionally, to meet the needs of practical engineering and applied projects, it is necessary to further improve specifications and standards, promote and apply mature fiber-reinforced composite material technology, and strengthen research in material testing, performance evaluation, and quality control.

3. State-of-Art Concerning Laminated Composite Materials in Structural Reinforcement and Resilience Enhancement

3.1. Effect of Changing the Deposition Order on the Properties of Laminated Composite Materials

Laminated composite materials are composite materials composed of two or more layers of different materials combined in a specific way, with good mechanical properties and various application fields. In order to further improve the strength and resilience of laminated composite materials, various new methods have been proposed, for example, changing the deposition sequence, adding synthetic fibers, interlayer reinforcement technology, design optimization, explosion-proof welding methods, etc. The deposition sequence and deposition materials are important factors affecting laminated composite materials. In recent years, many researchers have conducted experiments on material manufacturing and deposition sequence. Yang et al. studied 316L stainless steel in laminated composite materials and compared four laser scanning strategies. By using subtraction milling technology, they obtained a smooth surface and analyzed the average density, defects, average hardness, and tensile properties of the material. In addition, due to the clear interface of laminated composite materials, they also studied the possible residual stress, tensile anisotropy surface roughness, and internal defects that may exist during the manufacturing process of laminated composite materials through addition and subtraction hybrid manufacturing (HASM) [31–36]. Bhaburi et al. estimated the surface/interface quality, microstructure, and mechanical properties of hybrid aluminum parts, and improved their microhardness and joint strength through heat treatment [37]. In the field of laminated composite materials, SS316L and Inconel 718 alloy laminated composite materials are manufactured through mixed additives and subtraction to obtain materials with good mechanical and high-temperature properties. In addition, by studying the microstructure near the interface and the tensile properties in the deposition direction, it is possible to further understand the performance and feasibility of laminated composite materials. Li used HASM technology to manufacture laminated composite materials in one step and provides customized performance [38]. The improved additive manufacturing system and auxiliary traction milling can maintain a smooth and clear interface for energy deposition, solving the challenge of connecting different materials. The experimental results indicate that laminated composite materials with different deposition sequences have different microstructures and mechanical properties, among which IN718 laminated composite material deposited on SS316L exhibits the best performance, while new substances are generated at the interface between SS316L and 1040 steel to improve performance, as shown in Figures 7 and 8.

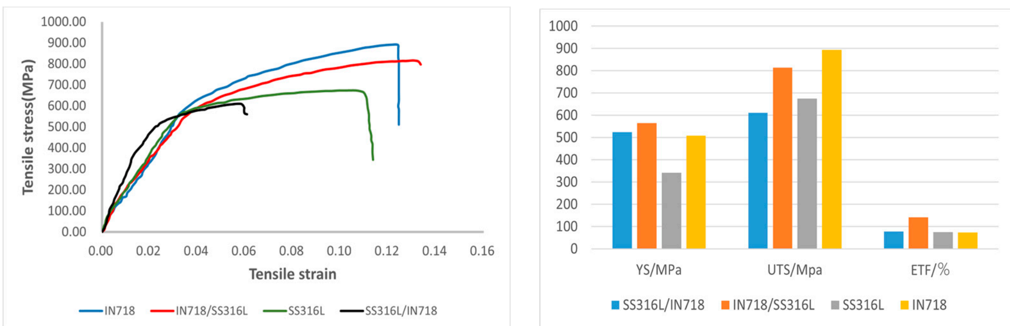


Figure 7. Tensile stress–strain curves for laminated composite specimens with different deposition sequences, manufactured by HASM (the initial calibration length was 20 mm).

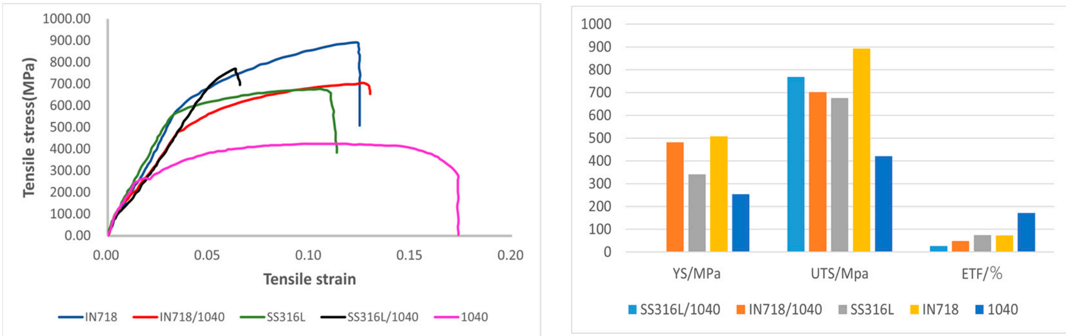


Figure 8. Tensile stress–strain curves for different materials deposited on 40 steel (the initial calibration length was 20 mm).

3.2. Methods for Improving the Performance of Laminated Composite Materials

In addition to the main method of changing the sedimentary sequence, many other new methods have been proposed in recent years. Kumar studied the preparation process for titanium alloy laminates for multilayer composite material input [39]. This study used a single stage process instead of rolling to prepare laminated plates, and investigated the sliding wear behavior of Ti-6Al-4V laminated plates. The research results indicate that composite materials have better wear resistance and lower wear rate than matrix materials, and the hardness value of composite materials is increased by about 25% compared to matrix materials. Biswas used the finite element method to study the effect of fiber orientation on the tensile, bending, and fatigue properties of bidirectional glass and carbon fiber-reinforced composite laminates [40]. The experimental results show that laminates with a laminate angle of (0°/90°) exhibit the maximum tensile strength, bending strength, and fatigue life. The tensile strength, bending strength, and fatigue life decrease with the increase in layer angle, and the layer angle reaches the minimum value (±45°). Therefore, the fiber orientation of composite materials can affect the quality of laminated materials. Liu introduced a test method for characterizing continuous fiber-reinforced composite materials, the deflection test, and its application in comparing the shear deformation of cross-unidirectional prepregs and woven prepregs [41]. This research has shown that material composition and different process parameters play a crucial role in the shear properties of composite materials, while the metal layer support can improve the shear deformation capability of fibers. This experimental method helps to better understand the process design in manufacturing hybrid metal composite laminates. Slattery emphasized the importance of robust residual strength testing methods for evaluating the effectiveness of composite laminate repair techniques [42]. The study used four different mechanical tests to study the strength of original, damaged, and repaired solid laminated composite materials, including post impact compression (CAI), tensile, and four-point bending tests. This research found that the different testing methods can affect the strength recovery capability of repair methods, and the four-point bending test is considered the best preliminary testing method for screening repair techniques. However, when selecting testing methods to evaluate the effectiveness of repairs, design standards should always be considered. Maithil introduced a methodology aimed at enhancing the mechanical properties of naturally reinforced fiber–polymer composites [43]. This approach primarily involves the synthesis of composite materials by combining reinforced fibers with polymer matrices. The purpose of the research was to improve the tensile strength of composites, and to achieve this goal by blending synthetic fibers into natural fiber. Using the ABAQUS software package for numerical construction and tensile simulation, the tensile behavior of composite material samples was evaluated, and the surface treatment was noted to improve the adhesion between fibers and matrix. The results show that the tensile strength of jute fiber is lower than that of hybrid fiber-reinforced composite materials, and the addition of carbon fiber can improve the strength of the laminate. Mortell described two highly coupled damage mechanisms in laminated composite materials—transverse microcrack growth and delamination [44]. This article investigates the effect of changes in transverse crack density on delamination growth. The results indicate that increasing the number of transverse layers can significantly improve the load-bearing capacity of the laminate. In addition, the article also discusses the use of new in situ scanning electron microscopy micromechanical testing and acoustic damage detection techniques to determine the initial load, density, and local differential layer length of transverse cracks, together with the performance and damage behavior of laminates under different loads. Zuo explored how to optimize the effective stiffness design for laminated composite materials [45]. By solving a constrained optimization problem, the laminated composites are designed by finding the best material properties of the constituent phases and their volume fractions. The findings of the research suggest that by identifying the ideal volume fraction for the constituent phases, it is possible to attain significant longitudinal and transverse stiffness. Additionally, enhancing Young's modulus in a specific stage leads to the attainment of the highest effective Young's modulus. These results indicate that the design and manufacturing of laminated composite materials have special effective stiffness, which can be easily achieved through the proposed methods and modern manufacturing technologies. Liu introduced an innovative technique that effectively examines interface strength within layered composite materials through the utilization of viscous elements [46]. This method also offers improved precision in forecasting the extent of the fracture process zone, particularly when employing coarse grids. This research has shown that the constant cohesion law is more suitable for simulation layering of coarse grids than the bilinear cohesion law. This method is applicable to different structural thicknesses and material properties. Li described that TC4/TA1/Ti6321 titanium alloy laminated composites were successfully fabricated by explosive welding, and the interfacial properties and dynamic mechanical properties were studied, as shown in Figure 9 [47]. The results show that there are high-density crystal defects at the interface, and the composite plate shows a hard/soft/hard hardness distribution, and the microhardness near it increases. Owing to the presence of interfaces, dynamic mechanical properties exhibit different results, and the failure mode is adiabatic shear failure mode. However, there are still some shortcomings in the new method for laminating composite materials. For example, although new technologies can improve the performance and reduce costs of composite materials, their actual preparation process may be limited by factors such as material cost, processing difficulty, and stability.

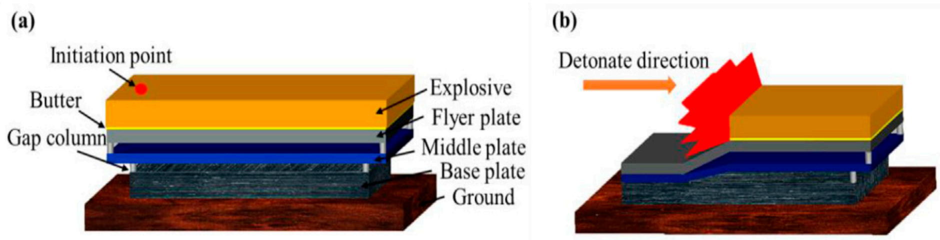


Figure 9. Schematic diagram showing the EXW experiment: (**a**) welding process design; (**b**) welding process at some point (adapted from [47]).

3.3. Modeling and Simulation for Optimization of Laminated Composite Materials

At present, models and software simulations have been widely established and applied toward laminated composite materials. Among them, finite element analysis and the genetic algorithm are the most commonly used methods, which can simulate the mechanical behavior of composite materials. In addition, multiscale simulation methods based on microstructure are gradually receiving attention, which can more realistically reflect the microstructure and mechanical properties of composite materials. Coelho described a computational model for designing bimaterial composite laminates using a multiscale topology optimization model to optimize the design of structures and materials [48]. The model is based on a hierarchical optimization strategy, taking into account the manufacturing process and basic characteristics, and using a mixed set of micro- and macrodesign variables to characterize the distribution of the two materials. This method has yielded better design results, which helps to provide a deeper understanding of the effectiveness of the microstructure characteristics of composite laminates. Shi employed the LS-DYNA software to simulate the dynamic and progressive failure process in laminated composite materials [49]. This simulation utilized the MAT_162 material models, encompassing factors such as strain rate, damage evolution, and anisotropy effects. To determine the model parameters, traditional standard and nonstandard testing methods were used, including double shear and Brazilian testing. Through experiments and numerical simulation, the fidelity of the developed material model parameters was verified, including the modulus and strength in plane and full thickness directions, fiber matrix splitting and shear fracture, and other failure modes. Nastos introduced a strength prediction method for composite laminates based on a combination of numerical and nondestructive testing, aiming to predict strength through nondestructive testing, as shown in Figure 10 [50]. In order to manage the difference between the maximum load of 20% and 100% in the sample, a high-fidelity physics-based numerical model, deep learning technology, and noncatastrophic experiments were used. This application is trained using convolutional neural networks and Monte Carlo dropout techniques, and validated using probabilistic failure analysis datasets generated by stochastic finite element methods.

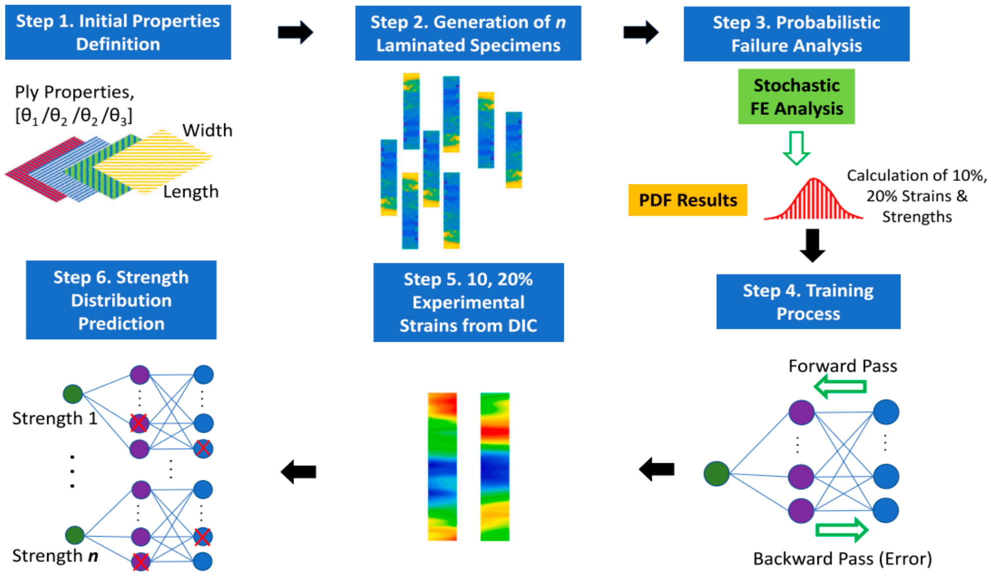


Figure 10. The concept of the nondestructive methodology for predicting strength in composite laminates (adapted from [50]).

Yashiro conducted a mode II interlaminar fracture resilience test (DENT) and examined it through elastic–plastic finite element analysis [51]. The aim was to explore the effect of material nonlinearity on the assessment of interlaminar fracture resilience within composite materials. The study revealed that the plastic zone size in the DENT test remains unaffected by the crack length. Furthermore, the disparity between the estimated energy release rate and the integration within the plastic zone size is relatively minor when compared to other quasi-static mode II interlaminar fracture resilience tests. The CC method is an effective way to evaluate the resilience of adhesives, and even significant plastic deformation does not affect the test results. These findings can be useful in evaluating the fracture resilience of laminated composite materials. Torabi described conducting experimental and theoretical crack investigations on laminated glass/epoxy composites to evaluate their load-bearing capacity [52]. By using a new concept called virtual isotropic material (VIMC) and combining predictions from two brittle fracture models, namely maximum tangential stress (MTS) and average stress (MS), the fracture behavior of laminated materials can be predicted. This prediction is necessary because laminated materials have complex structures and predicting their load-bearing capacity is difficult. The research results indicate that using

VIMC and LENFM filters to predict the load-bearing capacity of laminated materials can be directly, quickly, and conveniently predicted without the need for complex analysis. Lu proposed a three-dimensional separable cohesive element (SCE) that can simulate the interaction between matrix cracking and interface delamination in laminated fiber-reinforced composites [53]. The results indicate that SCE can effectively simulate stress concentration caused by matrix cracks and load transfer from solid components with cracks to interface viscous components. The application of SCE to the progressive failure model of composite laminates is consistent with experimental results. Lin proposed a framework for fast computation of low-speed impact analysis and compressive composite material impact response, using intelligent grid mode, effective modeling strategy, and the damage transfer algorithm [54]. This framework can significantly reduce computational time while maintaining accuracy, helping to expand design space and generate large databases. Compared with traditional methods, using this framework can reduce computational time by 67% and obtain prediction results within 6% error compared to experimental values. This framework can be used to optimize the impact resistance of laminated composite materials. However, there are also some limitations in establishing models and software simulations. First, the establishment of the model requires a large amount of experimental data for verification, which may be a significant challenge for composite materials. Second, existing models and software simulation methods often only consider the influence of a single factor and cannot fully consider the composite effects of multiple factors. Therefore, in the future, it is necessary to further develop and improve models and software simulation methods to better meet the needs in practical engineering.

3.4. Application of Laminated Composite Materials in Practical Engineering Projects

Changing the deposition sequence in technical methods can produce laminates with different resilience and tensile strength, and laminates manufactured using nanotechnology can be applied to very precise electrical components. The combination of new numerical values and nondestructive testing for strength prediction methods is of great significance for testing the performance of laminates, which is of great significance for practical applications. In recent years, there have been many new technological breakthroughs and practical applications in laminated composite materials. Among them, nanotechnology has been widely developed. One of the most effective uses of nanofibers or nanoparticles is as a staggered reinforcement for composite laminates, which can be embedded between two layers of laminates to study their effect on the overall performance of composite laminates. Bodduru studied the performance changes when E-glass fiber and sisal fiber were mixed together to manufacture laminates reinforced with epoxy polymer composites [55]. Researchers treated sisal fibers with alkali (NaOH) and made laminated samples using the manual lamination method. Additionally, they explored the effect of introducing carbon nanotubes (CNTs) and MXene ($Ti_3C_2T_x$) nanoparticles on hybrid composite materials. Nanofillers are mixed with pure epoxy resin and dispersed using ultrasound. The multiscale structure of MXene-dispersed hybrid plates was examined using scanning electron microscopy. The results indicate that by enhancing with 42% MXene, the tensile strength of sisal/glass fiber-laminated materials is enhanced. In addition, when MXene nanoparticles were used to enhance the matrix, the bending strength and modulus of sisal/glass fiber-laminated materials increased by 34% and 30%, respectively. This research found that the incorporation of nanofillers significantly improves the load transfer efficiency between the fiber material and the epoxy matrix, resulting in better elastic properties. Abot proposed the advantages and problems of fiber-reinforced polymer composites, namely the possibility of interlayer stress leading to premature failure [56]. To solve this problem, a composite material can be established between layers of laminated composite materials to maximize shear stress transfer. The dense arrangement of multiwalled carbon nanotube arrays is considered a nanoparticle-reinforced material that can improve the interlayer shear modulus of layered composite materials. The preliminary results indicate that this method is feasible. Ipackchi uses PVB electrospun nanomesa to toughen phenolic resin/glass fiber composite materials [57]. The experiment found that the thickness of the interlayer is the most effective factor in improving the resilience of type I and type II. Additionally, the decrease in nanofiber diameter and the increase in impact strength also contribute to the improvement in fracture resilience. The arrangement of nanofibers has little effect on the fracture of composite materials. High-tensile, ultrathin electrospun polyamide thermoplastic nanofibers were created, which were then incorporated into layers of glass fiber-reinforced woven phenolic preimpregnated composites. The experimental results indicate that an appropriate density of electrospun nanofibers can significantly improve the structural integrity of composite laminates without causing weight gain. There is a threshold for the density of nanofibers; exceeding this threshold will reduce the bonding performance between glass fibers and phenolic matrix [58]. Ji introduced a method of preparing nonwoven cellulose acetate nanofiber felt using electrospinning and adding it to the core layer of high-pressure laminates [59]. When the CA concentration is 16 wt.%, the morphology of the prepared CA nanofiber felt is the best. After adding CA nanofiber felt, the mechanical properties of the polymer composite material were significantly improved, including increased tensile strength and elongation at break. Kubin prepared low-density polyvinylidene fluoride (PVDF) nanocomposites containing cubic symmetric nano-$BaTiO_3$ using the electrospinning method, and the electron microscope image is shown in Figure 11 [60]. Brugo integrates nanopiezoelectric sensors into composite laminates to achieve self-sensing monitoring [61]. The composite laminate used is a composite material called glass-laminated aluminum-reinforced epoxy resin (GLARE). This nanostructured hybrid laminate is itself a piezoelectric sensor capable of detecting the effects on its entire surface. Nondestructive impact testing and research and optimization of circuit electrical parameters are used to evaluate the performance of self-sensing laminates, including linearity and spatial uniformity.

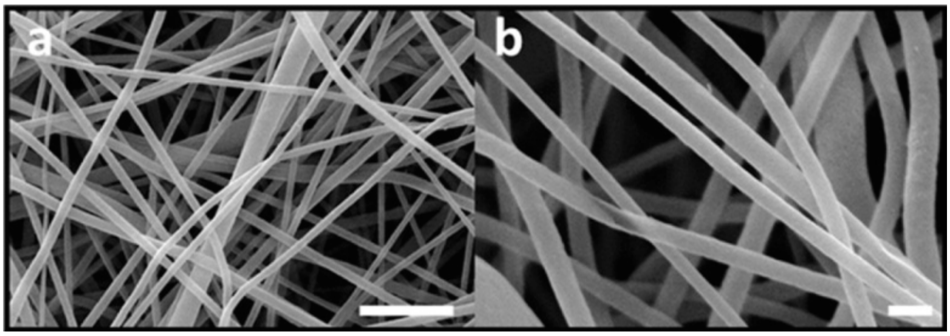


Figure 11. SEM images of electrospun PVDF/$BaTiO_3$ nanocomposite fibers: ES-PVDF (**a**,**b**). (adapted from [60]).

Palazzetti et al. reviewed the latest composite laminate technology, which interweaves electrospun nanofibers to enhance the material. The research in this literature adopts mechanical methods and focuses on the main load types. Researchers conducted in-depth research on the role and working mechanism of nanofibers and summarized the main results. The research results indicate that the nanofiber interlayer between the layers of the laminate can bring significant benefits from a structural and load-bearing perspective, while its impact on the weight and size of the laminate is minimal and even negligible. Compared with basic materials, the interlaced laminated sheets of nanofibers can significantly improve the mechanical properties of the material [62,63]. Xu introduced a multiunit-structured battery composite laminate composed of three advanced structural battery composite units in series [64] and studied its electrochemical and mechanical properties. The experimental results indicate that the capacity of the multiunit-structure battery composite laminate is slightly affected by tensile load. Additionally, after calculation and estimation, the mechanical properties of the multicore-structure battery laminated plate are equivalent to a traditional glass fiber composite multiaxis-laminated plate. Yoo examined the fundamental attributes and magnetoelectric potentials of a piezoelectric composite material consisting of

15 modules [65]. Additionally, Yoo crafted a structure with a magnetostrictive piezoelectric laminated plate to induce shear stress, employing the aforementioned material. The investigation also delved into the material's magnetoelectric properties. The research results indicate that this piezoelectric composite material has great potential for application in high-performance magnetic and electrical components. Although there are many new technologies and potential applications for laminated composite materials, there are still some limitations in practical applications. Compared to traditional materials, the damage and wear of laminated composite materials may lead to more complex repairs and higher maintenance costs. Therefore, it is necessary to comprehensively consider these issues when promoting and applying laminated composite materials.

4. State-of-Art Concerning Matrix Composite Materials in Structural Reinforcement and Resilience Enhancement

Matrix composite materials are composite materials composed of two or more different materials. One type of material is a matrix, and the other is a reinforcing material. This usually provides better performance and characteristics than a single material. Matrix composite materials are mainly divided into metal matrix composite materials and ceramic matrix composite materials.

4.1. Methods for Improving the Properties of Metal Matrix Composite

The strength and resilience improvement in metal matrix composite is one of the current research hotspots. Its new methods mainly focus on the stirring–casting method, material microstructure design, processing technology optimization, surface modification, and addition of appropriate second equalities. Rajaram studied the effect of particle weight fraction on the mechanical properties of metal matrix composite (MMC) by stirring–casting [66]. Metal matrix was prepared using aluminum (Al7075) and quarry rock dust powder, with 0%, 5%, and 7.5% rock powder and Al7075 added. Hardness, bending, and wear tests were conducted, and machining was carried out according to ASTM standards. This research found that the quarry stone powder of Al7075 has a higher hardness and lower wear rate, and the metal matrix containing 7.5 wt.% has the highest bending degree. Therefore, sample 2 has higher hardness and wear resistance. Rajaram studied the preparation of AA6063/ZrO_2 metal matrix composite by stirring–casting technology, and studied the mechanical properties of the composite through hardness, UTS, pin-on-disk wear, and other testing methods [67]. This research found that in the AA6063 sample of 4 wt.% ZrO_2 composite material, the maximum hardness is 71.0 HV and the maximum ultimate strength is 168.384 MPa, which is about 12% higher than the unreinforced AA6063 composite material. The results of the pin-plate wear test indicate that the lower wear rate identified in the AA6063 test sample with 4 wt.% ZrO_2 composite material is 2.5×10^{-6} mg/m. SEM microscopic testing confirmed that ZrO_2 particles were uniformly distributed in the test samples of 2 wt.% and 4 wt.% AA6063 composite materials. The research results indicate that as the weight percentage of ZrO_2 increases, the hardness and UTS of AA6063/ZrO_2 composite material significantly increase, while the wear rate significantly decreases. Chinababu successfully prepared two kinds of metal matrix composite, which are composed of different proportions of TiB_2 and CoCrFeMnNi high-entropy alloys [68]. The microstructure and morphology of the composites were studied by TEM and SEM. Compared with traditional ceramic particle composite materials, composite materials with added reinforcing phases have better mechanical properties, with LM25-2 wt.% TiB_2-3 wt.% HEA composite materials exhibiting the highest tensile strength. It was observed that with the increase in HEA content, the cleavage planes on the fracture surface changed. Xu successfully prepared carbon nano-onion (CNO)-reinforced AZ31B magnesium alloy composite MMC through friction stir treatment (FSP), and studied their microstructure and mechanical properties [69]. The experimental results indicate that FSP CNO/AZ31B MMC achieved a uniform fine-grained structure in the stirring zone, and the grain refinement mechanism is attributed to the continuous and discontinuous dynamic recrystallization, together with the key role played by CNOs in activating twinning behavior. The MMC exhibits enhanced yield strength and improved strain hardening ability, owing to a comprehensive effect of grain boundary strengthening, dislocation strengthening, Orowan strengthening, and the load-bearing mechanism of the reinforced material. Compared with the matrix material, the yield strength and elongation at break increased by 14% and 11.8%, respectively, indicating that both strength and ductility were improved due to the addition of CNO-reinforcement material. Zhai has developed a new method to manufacture metal matrix composite, that is, to use a three-dimensional metal glass lattice to strengthen metal [70]. This processing route overcomes the limitation in using only discontinued crystalline ceramic particles as reinforcing materials in existing methods. In the experiment, stainless steel matrix composites reinforced with 30% by volume, three-dimensional metallic glass in the form of a body-centered cubic lattice exhibited excellent mechanical properties. The enhanced mechanical properties mainly come from well-designed structures, good bonding between hard three-dimensional metallic glass and soft stainless steel, and their mutual reinforcement mechanisms. This study provides a novel design concept and manufacturing method that can be extended to other alloy systems to achieve improved mechanical properties. Kumar prepared Si_3N_4-reinforced Al7075 metal matrix composite (AMMC) by stirring–casting technology [71]. The results show that AMMC reinforced with Si_3N_4 has better hardness, tensile strength, compressive strength, and impact strength than the base alloy. The Si_3N_4 reinforced sample with a 9% weight percentage showed the best performance, and the predicted results of the regression equation were in good agreement with the experimental results. Therefore, stirring–casting is an effective method for preparing AMMC. Patil introduced a new microfilling material in metal matrix composite, namely fly ash [72]. This research has shown that adding different contents of fly ash can significantly improve the mechanical properties and wear resistance of aluminum alloy composite materials. SEM analysis also demonstrated the important role of the dispersion characteristics of fly ash in improving the performance of composite materials. These results show that it is feasible to use fly ash as a reinforcing material in metal matrix composite, and it has application prospects. Kumar has prepared powder reinforced metal matrix composite using traditional powder metallurgy methods, in which Al powder and ceramic particle reinforcement are an attractive combination [73]. The composite material prepared was subjected to hardness, compression, and tensile tests, and the seventh batch of samples was identified to have the highest strength. The aluminum grade, silicon carbide powder size, and weight fraction have an impact on the effective manufacturing of aluminum-based powder samples. Al SiC Gr is considered as a special composite combination with high strength to weight ratio and is an important metal matrix composite. Thirupathi compared the physical and mechanical properties under two different sintering cycles, and studied the density and microhardness [74]. By mixing 1% NbC powder with pure aluminum and compacting through conventional sintering and the Chu two-step sintering process (TSS-C), four samples were obtained, two of which were pure aluminum and two were Al-1% NbC. The results show that the mechanical properties of the TSS-C sample are better than the other samples, with higher density and microhardness, which is of great significance for the application of metal matrix composite in the automotive and aircraft industries. Sachin [75] studied the mechanical properties and specific wear rate of aluminum alloy Al6061 reinforced with different weight percentages of silicon carbide (SiC). Metal matrix composite were prepared by stirring–casting, and two SiC particles with different weight percentages were added into Al6061. The tests include tensile, hardness, and dry sliding wear, among which the C2 composite material shows higher wear resistance than the C1 composite material. Scanning electron microscopy was used to observe the microstructure of the composite material and determine the distribution of the reinforcement. The results indicate that SiC particles can adapt to specific wear applications, and the reinforcement has a strong impact on the matrix material. Meher prepared a TiB_2-reinforced magnesium RZ5 alloy matrix–in situ metal matrix composite by self-propagating high-temperature synthesis [76]. TiB_2 particles were nearly evenly distributed in the magnesium RZ5 alloy matrix. The solid solution heat treatment improved the mechanical properties of the material, with a maximum tensile strength of 178.7 MPa. Adding 8 wt.% TiB_2 can reduce the wear of the material. The microstructure of the composite material was observed through optical microscopy and field-emission scanning electron microscopy, and the wear surface of the composite material was analyzed. Gayathri introduced a new preparation method for metal matrix composite, which uses waste catalyst and copper oxide nanoparticles to strengthen the pure aluminum matrix [77]. The composite material was prepared by the double stirring–casting method, and the influence of different nano copper oxide contents on the mechanical properties of the composite material was investigated. The optimal composition was ultimately determined to be Al10% SAC1% nano copper oxide, which increased the hardness and tensile strength by 77% and 78%, respectively. Rahul studied the microstructure, mechanical properties, and texture evolution of AA6061-T6 metal matrix composites reinforced with silicon carbide (SiC) and zinc (Zn) particles during friction stir welding (FSW). The fracture diagrams of two particle-reinforced specimens are shown in Figure 12 [78]. Kumar studied the effects in the use of exfoliated graphite nanosheets and thermally sealed nanofillers on the mechanical properties of copper-based composites [79]. This research has shown that adding nanofillers can improve relative density, hardness, and wear resistance, while reducing porosity. The hardness and tensile strength of Cu-2 wt.% xGnP composite materials are higher than those of pure copper and Cu-MWCNT composite materials. In addition, the uniform distribution of xGnP and good adhesion to the copper matrix contribute to improving the mechanical properties and wear behavior of the composite material. Adding nanofillers can also change the crystal structure of composite materials. Although these new methods have improved the performance of metal matrix composite to a certain extent, there are still some problems and challenges, such as the loss of resilience while improving the strength, and the increase in material cost and manufacturing complexity due to alloying.

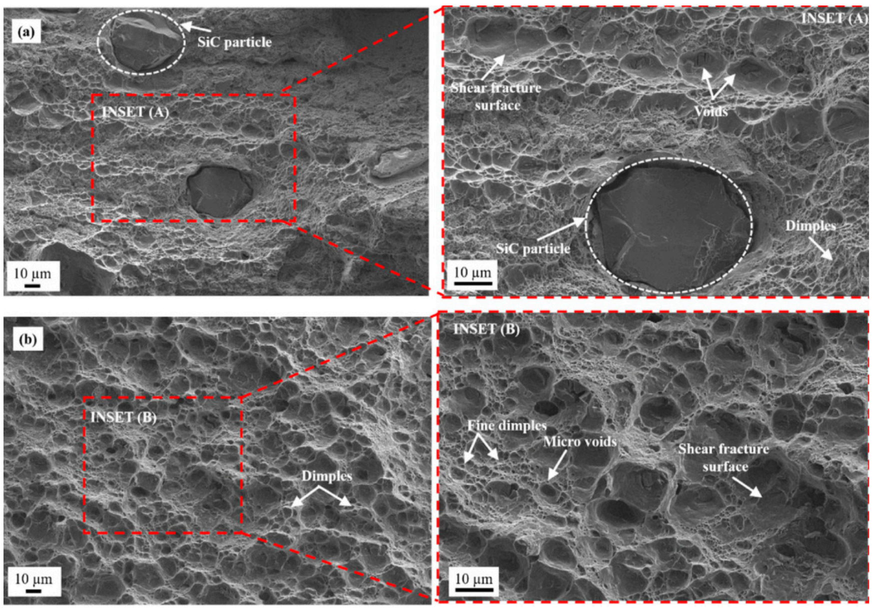


Figure 12. Fractography images of (**a**) SiC-particle reinforced and (**b**) Zn-particle reinforced tensile failure specimens (adapted from [78]).

4.2. Methods for Improving the Properties of Ceramic Matrix Composite

The strength and resilience improvement in ceramic matrix composite is one of the research focuses in the field of composites. Among them, using new methods to enhance strength and resilience is one of the main directions of current research, and common methods include nanoparticle reinforcement, adding new elements, microstructure regulation, and powder metallurgy, among others. Li found that the Nb content and sintering temperature significantly affect the phase formation and microstructure of the sample, while the width of the Ti_2AlC layered structure increases with the increase in sintering temperature [80]. The optimal compressive strength of Ti_2AlC MAX phase ceramic matrix composites was obtained under optimized Nb content (1 wt.%) and sintering temperature (1300 °C). This work demonstrates that LPBF and sintering methods can be used to design composite materials, and explores the properties of Ti_2AlC MAX phase ceramics from the perspective of microalloying. Xi investigated the effect of mixed ceramic reinforcement content on the mechanical properties of aluminum matrix composites [81]. They used laser powder bed fusion to prepare composites reinforced with different contents of (ZrC TiC) ceramic fractions. The results showed that with the increase in mixed ceramic content, the laser absorption behavior of the composite material is enhanced, and the fraction of nanoparticles increases. The composites containing 20 wt.% ceramics exhibited high micro- and nanohardness, and the elastic modulus and tensile strength of 15 wt.% (ZrC + TiC)/Al composite material were significantly higher than the unreinforced Al matrix, due to the formation of nanoprecipitates and coherent binding at the reinforcement/matrix interface. Yao predicted the effective elastic properties of conductivity of 3D printing materials and the mechanical properties of ceramic matrix composite using micromechanical models and resistance network models [82]. The study considers the hierarchical structure of two scales, and uses an appropriate model to homogenize each scale, which can be applied to alumina ceramic matrix composite containing multiwall carbon nanotubes. Through parameterization research, it was found that the electromechanical properties of composite materials are sensitive to geometric features related to machining. This study provides a method for predicting effective electromechanical performance, which can evaluate the electromechanical performance of composite material parts. Galizia compared the microstructure and mechanical properties of different ZrB_2-based composites prepared by slurry infiltration sintering (SIS), polymer infiltration pyrolysis (PIP), and radio-frequency chemical-vapor infiltration (RF-CVI) processes, and evaluated the structural properties of these composites [83]. High temperature tensile tests were conducted on an ultrahigh temperature hot carrier trap, and the results showed that different porosity and fiber properties have varying degrees of influence on the mechanical properties of the composite material. All ZrB_2-based CMCs exhibit excellent structural performance at high temperatures. Additionally, the role of high-level residual thermal stress was also discussed. Wang introduced a new method to predict the fracture resilience of granular ceramic matrix composite at high temperatures [84]. This method uses the stress intensity factor method and high-temperature fracture strength theory, taking into account the effects of internal and surface defects, laminated structures, and thermal residual stresses inside particles and laminated materials, without the need for traditional destructive experiments. The predicted results are in good agreement with the measured data, therefore providing an effective method to obtain the high-temperature fracture resilience and fracture strength for multilayer and particle composites. Wang prepared three types of ceramic particle-reinforced iron matrix composites using the powder metallurgy method, namely alumina/Fe45, ZTA (zirconia-toughened alumina ceramic particles)/Fe45, and zirconia/Fe45 [85]. This paper studied their mechanical properties, impact abrasive wear resistance, and impact abrasive wear mechanism, and found that ZTA/Fe45 composite materials have better wear resistance. In the phase transition analysis of composite materials and ceramic particles, the t-ZrO_2 to m-ZrO_2 phase transition increases the resilience of ZTA and improves the wear resistance of ZTA/Fe45 composite materials. Xiang used the HQEM method to predict the working pressure of unidirectional fiber-reinforced ceramic matrix composite, and determined the CMC interface properties damaged by micromachining by analyzing sensitivity and optimal parameters [86]. The results indicate that compared to the classical shear model, the HQEM method has higher accuracy in verifying pressure distribution. Additionally, the study analyzed micromechanical behavior through three typical cases and provided insights into the microstructure behavior related to composite material failure characteristics and global failure mechanisms. This study provides a promising method for effectively analyzing the fracture of CMC. Yu studied transverse tensile mechanical experiments using ceramic matrix microcomposite materials (CMMC) [87]. Digital optoelectronic technology was used in the experiment to analyze the evolution process of the strain field and study the uniformity changes in the transverse tensile strain field. There is a strong correlation between the uniformity of the strain field and the degree of damage, which can sensitively reflect the damage evolution process of materials. The relationship between local damage and overall mechanical response, along with the localization and nonuniformity characteristics of damage evolution, were discussed. Additionally, the influence of microstructure on the transverse tensile modulus of CMMC was analyzed, and a prediction model for transverse tensile modulus of CMMC considering microstructure was established. Chen prepared Ti_3SiC_2/SiC ceramic matrix composite through molten salt synthesis and subsequent polymer infiltration and pyrolysis techniques, as shown in Figure 13 [88]. Compared with PDC SiC, this composite material has higher mechanical properties, electromagnetic interference shielding effect, and thermal conductivity, due to its preformed Ti_3SiC_2 connecting to the network skeleton. The flexural strength and fracture resilience of the composites have good properties.

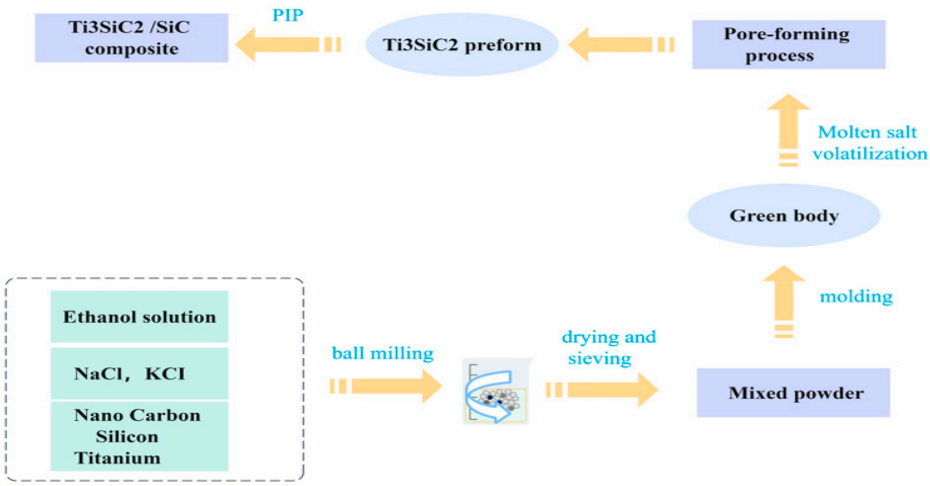


Figure 13. The preparation process diagram for Ti_3SiC_2/SiC composites.

Li successfully synthesized ceramic-reinforced 316L/IN718 matrix composites in situ through directed energy deposition technology [89]. The study compared the microstructure, microhardness, tensile properties, and wear resistance of metal matrix composite materials with unreinforced samples. It was found that when 10% Ti was added, the microhardness increased to 629.6 HV, the ultimate tensile strength increased to 717.9 MPa, and the friction coefficient decreased to 0.688. This study provides a practical and economical method for preparing 316L/IN718-Ti composite materials as potential high-strength and wear-resistant materials. Farvizi studied the use of YSZ particles with the coefficient of thermal expansion close to NiTi alloy as reinforcement materials to improve the wear resistance of NiTi alloy [90]. By using YSZ instead of monoclinic zirconia as a reinforcing agent, lower mismatch stress can be generated. Therefore, there is still a high proportion of austenite phase in the matrix, which has strain recovery ability and is beneficial for the application of tribology. Therefore, NiTi YSZ samples with a higher proportion of austenite and better mechanical properties have superior wear resistance. The wear mechanism is mainly dominated by abrasive, delamination, and adhesion mechanisms. The research results indicate that ceramic-based materials can provide excellent performance to meet various application needs. In general, there are still some defects in the strength and resilience improvement in ceramic matrix composite, such as high processing difficulty and high cost.

4.3. Application of Matrix Composite Materials in Practical Engineering Projects

Matrix composite materials have a wide range of applications due to their special properties, and have been applied in recent years in biomedical, biodegradable, brake pads, radiation shielding, and other related fields. Manso studied how to improve the wear resistance of metal bone implants by adding hard reinforcements [91]. Studying the use of nontoxic and nonallergenic β, two different in situ composite materials were prepared by adding NbC powder to Ti-Nb alloy as the matrix material. This strategy can achieve the synthesis of reinforcing phases during the manufacturing process and achieve strong interface bonding through high chemical compatibility. The results showed that the friction and corrosion properties of both composite materials were improved, and the wear amount was less than 50%. These results indicate that the matrix composite material is a potential bone implant material that can improve its wear resistance and degradation process. Kabir's study introduced a zinc-based composite material for biodegradable implant materials, which added graphene nanosheets to improve its mechanical properties and corrosion behavior [92]. The research results show that the composite material has high mechanical properties and good biocompatibility, making it a potential biodegradable implant material. In the past few years, carbon ceramic brakes have been favored for their light weight, high-temperature resistance, and long lifespan. Bianchi's research analyzed the environmental impact of carbon ceramic brakes using a lifecycle assessment method, and the specimen implementation program is shown in Figure 14. The results show that although cast iron brakes are more sustainable in the production stage, carbon ceramic brakes prepared from recycled prepreg waste have lower environmental impacts in long-term use [93]. Bhakuni described the development of granular ceramic matrix composite (PCMC) for automobile brake pads prepared by two powder metallurgy methods [94]. The first type shows good density, thermal stability, and low noise, while the second type shows excellent properties such as high scratch hardness. This study indicates that these two PCMC samples outperform traditional commercial brake pads in terms of performance, demonstrating potential effective performance in practical use. Suna introduced a preparation method for low-density polyethylene (LDPE)-based composites using boron carbide, dysprosium tetraborate, dysprosium oxide borate, and boron carbide dysprosium compounds as reinforcing materials [95]. The chemistry, mechanics, morphology, thermal properties, and neutron radiation shielding performance of composite materials were studied in this work. The research results indicate that composite materials not only have effective neutron shielding performance, but also have performance comparable to pure boron carbide LDPE-based composite materials. This composite material has potential for safe applications that require protection from neutrons and gamma rays.

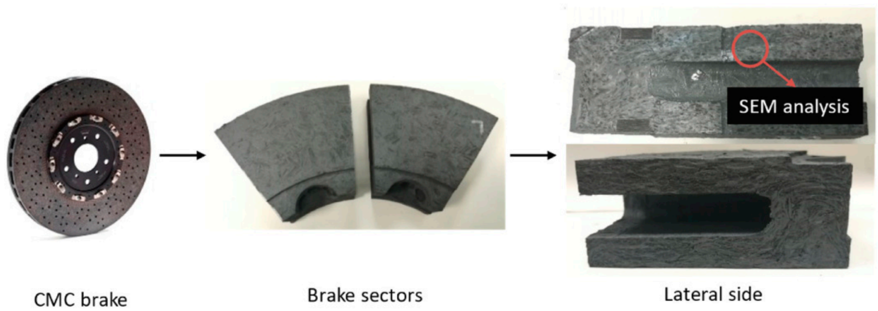


Figure 14. Procedure for specimen realization for SEM analysis (adapted from [93]).

5. State-of-Art Concerning Other Composite Materials in Structural Reinforcement and Resilience Enhancement

In addition to the advanced composite materials mentioned above, there are also many other advanced composite materials, such as viscoelastic materials, magnetorheological fluids, and concrete mortar. These advanced composite materials have excellent applications in certain single fields. Viscoelastomers and magnetorheological variants can be used to make dampers for vibration reduction control of structures, and improved concrete mortar can be used for reinforcement and resilience improvement in building structures.

5.1. Theoretical Research and Practical Application of Viscoelastic Materials

Viscoelastic materials have characteristics such as elastic behavior, noninstantaneous deformation, and viscosity, making them the main materials for manufacturing viscoelastic dampers. Xu developed viscoelastic materials based on different matrix rubbers and conducted experiments [96]. The results indicate that the viscoelastic damper based on a nitrile rubber matrix has high energy dissipation capacity, while the viscoelastic damper based on a silicone rubber matrix has stable performance under different working conditions. To elucidate its mechanical properties, an equivalent high-order fractional derivative model considering temperature and frequency effects was proposed, and numerical results consistent with experimental results were obtained. Xu introduced the application of viscoelastic dampers in seismic reduction [97]. Firstly, the mathematical model of VE dampers and the dynamic analysis of structures with VE dampers were introduced. Then, an equivalent standard solid model is used to describe the effect of temperature on the energy absorption characteristics of VE dampers. Finally, the response of a three-story reinforced-concrete frame structure with and without VE dampers was studied through elastic–plastic time field analysis, frequency field analysis, and shaking table tests. The results showed that VE dampers can be modeled using an equivalent standard solid model, and are effective in reducing structural seismic response. Xu introduced the preparation and performance testing of acrylic viscoelastic dampers [98]. On the basis of acrylic rubber molecules, the optimal formulation of viscoelastic dampers was prepared and mechanical properties were tested. The performance of the damper under different temperatures, excitation frequencies, and displacement amplitudes was studied, and it was found that it has good damping performance and is influenced by environmental temperature and excitation frequency, while the energy dissipation capacity of a single circuit is significantly affected by displacement amplitudes. In order to accurately represent these effects, a modified fractional derivative equivalent model was introduced and compared with experimental data to verify the correctness of the mathematical model. Xu proposed a high order fractional derivative model and temperature frequency equivalence principle to characterize the effects of frequency and temperature, and introduced internal variable theory to consider the effect of internal/microscale structure evolution on capture displacement [99]. The mechanical properties of a plate shear-type viscoelastic damper under sinusoidal displacement excitation at room temperature have been tested, as shown in Figure 15, and it has been proved that the high-order fractional derivative model modified using the internal variable theory and the temperature frequency (0.1–25 Hz) equivalence principle (ITHF) is sufficiently accurate in describing the dynamic behavior of viscoelastic dampers with different frequencies and displacement amplitudes.

$$G_1 = k_1 \left\{ \begin{array}{l} \mu_1 + \eta_1(\alpha_T\omega)^\gamma \cos(\gamma\pi/2) \\ + \frac{\mu_2 c_2(\alpha_T\omega)^\beta \cos(\beta\pi/2) + \mu_2(\alpha_T\omega)^{\alpha+\beta}\cos[(\alpha-\beta)\pi/2]}{c_2^2 + 2c_2(\alpha_T\omega)^\alpha \cos(\alpha\pi/2) + (\alpha_T\omega)^{2\alpha}} \end{array} \right\} \frac{1}{1+(\varepsilon/\varepsilon_c)^{2m}+b_1}$$

$$G_2 = k_2 \left\{ \begin{array}{l} \eta_1(\alpha_T\omega)^\gamma \sin(\gamma\pi/2) \\ + \frac{\mu_2 c_2(\alpha_T\omega)^\beta \sin(\beta\pi/2) + \mu_2(\alpha_T\omega)^{\alpha+\beta}\sin[(\beta-\alpha)\pi/2]}{c_2^2 + 2c_2(\alpha_T\omega)^\alpha \cos(\alpha\pi/2) + (\alpha_T\omega)^{2\alpha}} \end{array} \right\} \frac{2(\varepsilon/\varepsilon_c)^m}{1+(\varepsilon/\varepsilon_c)^{2m}+b_2}$$

The higher-order fractional derivative model modified after the Kraus model and temperature–frequency equivalence principle (KTHF) is shown above.

Xu introduced the common applications of viscoelastic dampers as passive control devices for structural vibration reduction, and mentioned that their energy dissipation characteristics are influenced by temperature and frequency [100]. To describe the complex characteristics of this damper, a new model, the equivalent standard solid model, was proposed and applied to the comparison of experimental and numerical data. At the same time, the author applied 52 viscoelastic dampers to the seismic reinforcement design of Xi'an Petroleum Hotel, and conducted finite element analysis on the structures with and without dampers. The results indicate that viscoelastic dampers can effectively reduce seismic response and are a high-performance energy dissipation device, as shown in Figure 16.

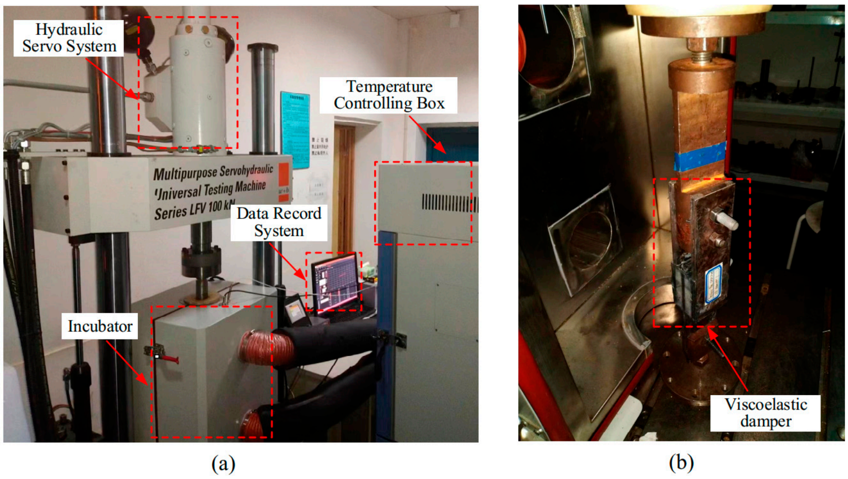


Figure 15. Equipment for testing the dynamic properties of a viscoelastic damper: (**a**) schematic image; (**b**) viscoelastic damper inside the incubator (adapted from [95]).

Figure 16. Viscoelastic vibration reduction device for the Xi'an Fujin JiaYuan building apartment.

5.2. Theoretical Research and Practical Application of Magnetorheological Materials

Magnetorheological fluid has the characteristics of adjustability, fast response speed, small size, and light weight, making it the main material for manufacturing magnetorheological dampers. Xu conducted research on magnetorheological fluids and their composite materials [101]. Magnetorheological fluid is an intelligent material widely used for structural vibration reduction, consisting of iron particles, carrier fluid, and additives. One of the research hotspots is the expectation that ferromagnetic particles have low density and high magnetic properties. This article uses ultrasonic and mechanical stirring–grafting techniques to coat multiwalled carbon nanotubes (MWNT) onto carbonyl iron (CI) particles;

an electron microscope image is shown in Figure 17. In addition, shear yield stress tests were conducted on self-made composite materials, and the test results were compared with the theoretical values of the single- and double-chain micromechanical model to verify the effectiveness and accuracy of the proposed model. Xu discussed how to control the vibration response in aerospace or precision instrument platforms in the frequency range of 0 to 500 Hz [102]. A new scheme using vibration isolation and damping devices, magnetorheological dampers, and viscoelastic dampers has been proposed. The dynamic response of these dampers under different excitations was calculated by coupling the motion equations of the vibration model, and the multistate control concept was adopted to control the input current of the magnetorheological damper. The experimental results show that the scheme is effective and suitable for vibration control of the platform [103]. Xu designed and manufactured a new type of high-damping vibration isolation and damping device, aimed at reducing the dynamic response of the platform over a wide frequency range. After testing, the effect of excitation frequency and amplitude on the properties of the device was considered. Additionally, a platform dynamics model for vibration isolation and damping devices was established, and the dynamic response of the damping platform under different excitations was calculated. By comparing the time-domain and frequency-domain responses of damped and undamped structures, it was concluded that these devices can significantly reduce the dynamic response of the platform.

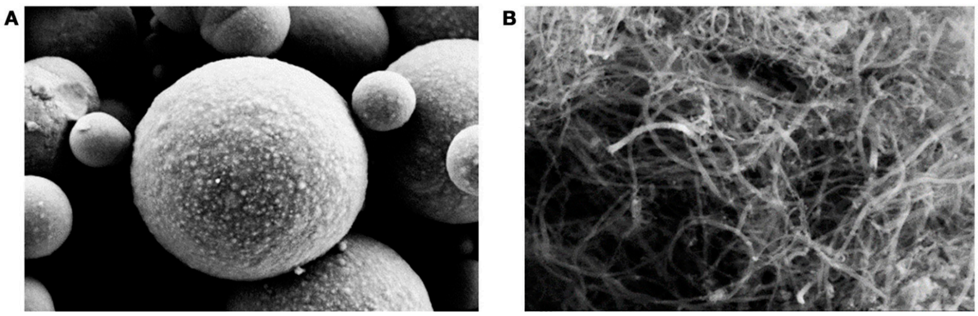


Figure 17. The electron micrographs of (**A**) original CI particles and (**B**) MWNTs (adapted from [101]).

Xu introduced a new hybrid testing system based on Matlab OpenSees combination programming, which is used for hybrid testing of seismic response of structures [104]. The feasibility and accuracy of the hybrid experimental system have been demonstrated by verifying the performance of the testing equipment and Matlab OpenSees system, and testing the mechanical properties of viscoelastic dampers under different conditions. In addition, through mixed experiments on three-dimensional viscoelastic damping structures, it was verified that viscoelastic dampers have good damping effects on structures under seismic excitation. Compared with previous hybrid testing systems, this system has a wider range of applications and can achieve more accurate seismic response testing. Xu uses magnetorheological dampers to carry out semiactive control of buildings and structures to reduce earthquake damage [105]. The article proposes a Bingham model for magnetorheological dampers and proposes a relationship between the yield shear stress and control current of magnetorheological dampers that matches the experimental data. Then, an online real-time control method for semiactive control of MR damper structures was introduced, which can solve the problem of structural response distortion. Finally, an example was used to verify the effectiveness of online real-time control. Xu introduced the characteristics of magnetorheological dampers as a semiactive control device, particularly highlighting the application of magnetorheological elastomeric composites, as shown in Figure 18 [106]. The magnetic saturation problem of magnetorheological dampers is an important research direction. This article describes experimental and simulation research on shear valve-type magnetorheological dampers, proposes a mathematical model of magnetic saturation, and compares it with other models. The magnetic-saturation mathematical model can describe the effects of input current, displacement amplitude, and excitation frequency on the property and magnetic saturation performance of magnetorheological dampers, providing important references for the development and application of magnetorheological dampers.

Figure 18. MR dampers for Hanzhong City West Second Ring Bridge (images by Zhao-Dong Xu).

However, there are still some shortcomings in the current research. First, the preparation process and technology of composite materials need to be further optimized and improved to increase their performance. Second, the viscoelastic and magnetorheological properties of composite materials have a significant impact on their preparation and application, and require in-depth research.

5.3. Performance Improvement and Practical Application of Concrete Mortar Composite Materials

Concrete and mortar composite materials are widely used in the construction industry, and their strength and resilience are key factors affecting their performance. In recent years, researchers have proposed various new methods to improve the strength and resilience of concrete and mortar composite materials, for example, the addition of nanomaterials, the use of additives, and microstructure regulation. Malakopoulos and Salifoglou studied the properties of mortars composed of Portland limestone cement, calcium carbonate, butyl stearate, and oleic acid [107]. The results indicate that compared to ordinary Portland limestone cement mortar, adding calcium carbonate, butyl stearate, and oleic acid to the mortar mixture can improve durability. The use of alkaline activators to chemically polymerize aluminosilicate materials for the production of alkaline-activated materials can effectively reduce greenhouse gas emissions from ordinary Portland cement (OPC) (approximately 73%). In order to solve the treatment problem concerning silicon manganese slag, Luo et al. used silicon manganese slag in alkali-activated materials to replace the original slag composition; an electron microscope image is shown in Figure 19 [108]. Through research, it has been proven that the flowability, setting time, compressive strength, flexural strength, microstructure, and freeze–thaw resistance of alkali-activated silicon manganese slag concrete (AASSC) have been improved under different ratios, steel-fiber volume fraction, and alkali-activation modulus (MS). Cheng studied the effects of various toughening materials on the resilience of concrete and mortar [109]. A variety of toughening materials, including PVA fiber, rubber particles, and polymer latex powder, were prepared using specific specimens, and their bending and compression properties were tested. The results indicate that mixing multiple toughening materials can greatly improve the bending resilience for mortar and concrete compared to adding only PVA fibers. From the scanning electron microscope images, it can be seen that the incorporation of mixed toughening materials can promote the formation of network structures and improve crack resistance. Ohemeng used waste concrete powder and fly ash as cement substitutes to produce mortar, exploring their combined effects, environmental impact, and cost analysis [110]. The study was conducted in two stages. The first stage replaced cement with 0%, 15%, 40%, 60%, and 100% waste concrete powder, while the second stage added 0% to 25% fly ash at a ratio of 40% waste concrete powder and 60% cement. The experimental results indicate that the performance of the produced mortar improved and met the strength requirements for masonry engineering. Additionally, the use of fly ash can reduce costs and electrical resistivity, and has good economic and environmental benefits.

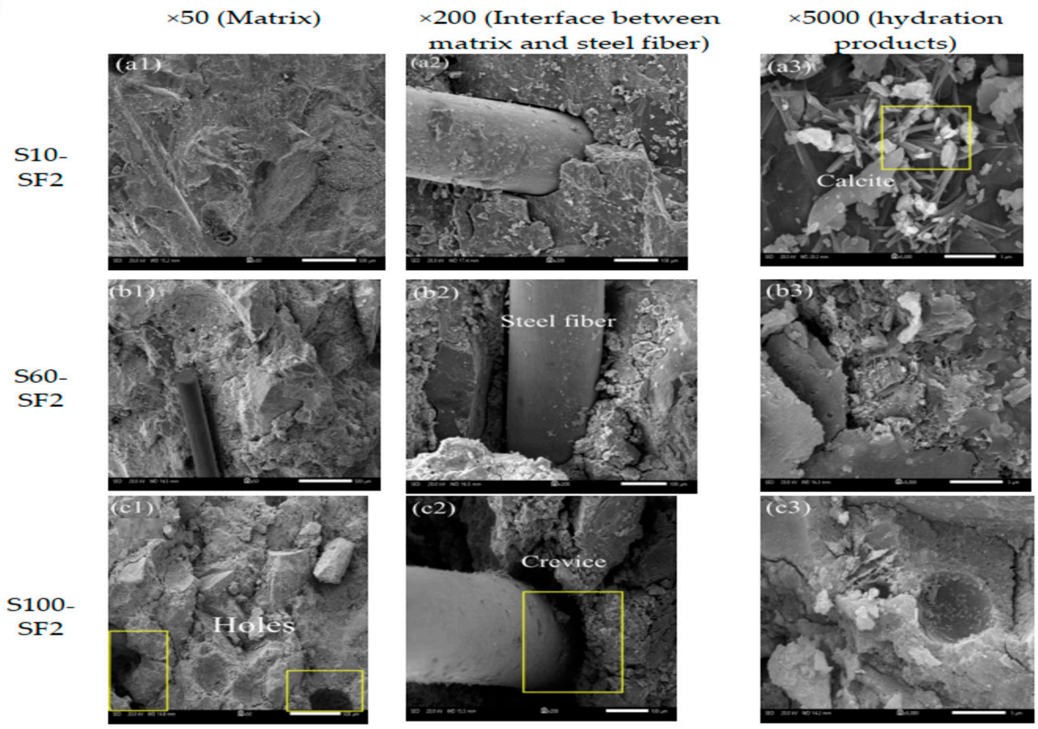


Figure 19. SEM images of AASSC with different substitution ratios of silicomanganese slag: (**a1**–**a3**) S10-SF2 (**b1**–**b3**) S60-SF2 (**c1**–**c3**) S100-SF2 (adapted from [108]).

Dobiszewska studied the effect of concrete production on the environment and used waste byproducts as substitutes for clinker [111]. Rock dust is considered a potential alternative material for the production of cement composite materials. However, there are conflicting findings in the literature regarding the effect of partial substitution of cement on the physical and mechanical properties and durability of cement composite materials. The effect of using rock dust instead of cement is mainly related to the filler effect. The higher the amount of replacement cement, the lower the mechanical properties and durability of cement composite materials. However, replacing cement with up to 10–15% rock powder will not affect the performance of cement composite materials. Sara uses construction and demolition (C&D) waste instead of natural sand, and uses ground and granulated blast furnace slag (GGBFS) instead of cement to manufacture self-compacting mortar [112]. The research results indicate that using recycled concrete sand (RCS) instead of natural sand can produce self-compacting mortar, with an optimal yield of 50%. Replacing cement with GGBFS can offset the negative effects of mortar porosity and capillary water absorption, and improve long-term compressive strength. By adding hydrated lime to mortar, Zhang studied the effect of hydrated lime on the mechanical properties of ultrahigh-performance concrete mortar and analyzed its impact mechanism through microstructure testing [113]. The results show that under the conditions of hot-water curing and dry-air heating, different proportions of hydrated lime can improve the mechanical properties of mortar, because the generated (C-(A)-S-H) gel is transformed into crystalline gabbro and xonotlite, and the microstructure is refined. Additionally, when the volcanic ash reaction and cement hydration reach an optimal balance, the mortar containing higher crystalline phases has a denser microstructure and better mechanical properties. Pan uses an encapsulated silane coupling agent (SCA) to modify the surface of waste polyvinyl chloride (PVC) particles to improve the performance of concrete and mortar [114]. The results showed that after SCA modification, the compressive strength and flexural strength of concrete and mortar were both improved. Scanning electron microscopy observation showed that SCA improved the bonding between PVC particles and cementitious materials, thereby improving the mechanical properties of the mortar. Liu recycled the ground concrete waste powder to prepare a green binder, and prepared a highly sustainable metakaolin-based polymer mortar [115]. Adding concrete waste powder into metakaolin can improve the dry shrinkage and compressive strength, but also affect the microstructure and the amount of the cement-based composite geopolymer slurry product. By optimizing the type and amount of concrete waste powder, the sustainable metakaolin-based polymer mortar with high strength and poor conveying performance can be prepared. Although these methods have achieved certain research results, there are still some shortcomings in practical applications, such as the high expense of the added materials, complex production processes, and the ability to only improve a single performance.

6. Conclusions

Advanced composite materials, such as fiber-reinforced composites, laminated composites, matrix composites, and other advanced variants, possess distinct advantages in enhancing structural reinforcement and improving resilience. The main representatives of fiber-reinforced composite materials, CFRP and GFRP, are characterized by their light weight and high strength, and are widely used in civil engineering, aerospace, and automotive industries. Laminated composite materials can exhibit excellent crack resistance and resilience by changing the deposition sequence and optimization modeling, and are widely used in fields such as electrical components and piezoelectric sensors. The addition of nanoparticles or fiber-reinforced materials to the matrix enhances the performance of the matrix itself. It has good structural reinforcement effect, while also providing a certain degree of resilience and durability, and is widely used in fields such as construction and shipbuilding. Other advanced composite materials, such as viscoelastic materials and magnetorheological fluids, are very good energy dissipation materials with good resilience, and are widely used in the production of dampers and applied in other engineering fields. They are of great significance for seismic reduction and reinforcement of buildings.

(1) For fiber-reinforced composite materials, current research mainly focuses on developing new methods, establishing models, optimizing algorithms, and creating new applications. The new methods mainly focus on controlling and enhancing fiber orientation, modifying surfaces, crosslinking, using additives, and applying mixed fibers. The models and algorithms focus on multiscale topology optimization, genetic algorithms, prediction models, etc. New applications are concentrated in fields such as aerospace, construction, electronics, shipbuilding, etc., such as bonding with concrete beams as reinforcement materials, pump impellers, natural gas transport ships, brake pads, etc.

(2) For laminated composite materials, the current research mainly focuses on developing new methods, establishing models, and optimizing algorithms. The new methods mainly focus on changing the deposition sequence, using finite element comparative analysis, applying interlayer reinforcement technology, and, especially, adding nanofibers, which has become a new research hotspot. The establishment of models and optimization algorithms mainly focus on finite element analysis, multiscale simulation, genetic algorithms, etc.

(3) For matrix composite materials, matrix materials can be mainly divided into metal and ceramic matrix composites. At present, research on new methods mainly focuses on stirring–casting, secondary addition of new elements, microstructure regulation and optimization, and nanoparticle reinforcement. Additionally, quantitative analysis and performance optimization of matrix composite materials can also be achieved through methods such as establishing models and optimization algorithms.

(4) For other composites, these mainly include materials such as magnetorheological fluids, viscoelastic materials, concrete mortar, etc. The main application of magnetorheological and viscoelastic materials is to produce dampers for vibration reduction and seismic resistance in buildings and various precision instruments. The strength and durability of concrete mortar has been greatly improved by including additives

and toughening materials, which are of great significance for their application in construction engineering.

The development of advanced composite materials in structural reinforcement and resilience improvement has made much progress, but there are still some developmental deficiencies, for example, their high cost, immature processes, and practical application in extreme environments. Further research and development are still needed in the future.

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