International Journal of Research in Advanced Engineering and Technology
www.allengineeringjournal.in
ISSN: 2455-0876
Received: 02-02-2026, Accepted: 01-03-2026, Published: 18-03-2026
Volume 12, Issue 1, 2026, Page No. 32-41

Evaluating the structural and electromagnetic performance of graphene-enhanced carbon-fiber composites for aerospace applications

Ajay Kumar Singh, Dr. Rajesh Rathore
Department of Engineering, Vikrant University, Gwalior, Madhya Pradesh, India

Abstract

The escalating demand for lightweight and multifunctional materials in aerospace engineering has catalyzed significant research toward next-generation composite materials capable of providing both structural performance and electromagnetic protection. Carbon fiber reinforced polymer (CFRP) composites are extensively utilized in aerospace structures due to their elevated strength-to-weight ratio, corrosion resistance, and fatigue durability. However, conventional CFRP materials exhibit limitations in electrical conductivity and electromagnetic interference (EMI) shielding capability, which are critical for protecting sensitive onboard electronic systems. The incorporation of graphene nanomaterials into carbon fiber composites has emerged as a prospective strategy for augmenting both mechanical and electromagnetic properties of these composite materials. This study presents a literature-based comparative analysis evaluating the structural and electromagnetic performance of graphene-enhanced carbon fiber composites for aerospace applications. The analysis synthesizes findings from peer-reviewed studies to compare conventional CFRP materials and graphene-reinforced composites in terms of tensile strength, impact resistance, electrical conductivity, and EMI shielding effectiveness. The findings reported in the literature indicate that graphene incorporation significantly improves mechanical performance through enhanced fiber–matrix interfacial bonding, crack-arrest mechanisms, and improved stress transfer within the composite structure. In addition, graphene nanosheets form conductive networks within the polymer matrix, enabling effective attenuation of electromagnetic radiation through reflection, absorption, and multiple internal scattering mechanisms. Overall, graphene-enhanced carbon fiber composites demonstrate superior multifunctional performance compared with conventional CFRP materials, offering significant potential for lightweight aerospace structures requiring both structural integrity and electromagnetic shielding capability.

Keywords: Graphene composites, carbon fiber reinforced polymers (CFRP), electromagnetic interference (EMI) shielding, impact resistance, lightweight aerospace materials, graphene-reinforced composites, multifunctional composite materials

Introduction

The aerospace, automotive, and defence industries increasingly demand advanced materials that offer high structural performance while minimizing overall weight. Lightweight materials play a vital role in optimizing fuel efficiency, controlling emission output, enhancing payload capacity, and increasing operational efficiency in modern engineering systems. In aerospace applications, reducing structural weight directly contributes to lower fuel consumption, extended flight range, and improved aerodynamic performance. Similarly, in automotive and defence sectors, lightweight yet durable materials improve vehicle efficiency and operational mobility while maintaining structural safety (Bhavya *et al*., 2020; Adeleke *et al*., 2024) [1, 5].

Traditional metallic materials for instance aluminium alloys, titanium alloys, and high-strength steels have long been used in aerospace structures because of their mechanical strength and durability. However, these materials often face limitations related to density, corrosion resistance, and fatigue performance (Schutz & Grauman, 1986) [30]. Consequently, composite materials have increasingly replaced conventional metals in many structural implementations owing to their exceptional strength-to-weight ratios and improved fatigue resistance (Baker *et al*., 2004; Soutis, 2005; Campbell, 2010) [3, 6, 34]. Modern aircraft structures increasingly rely on fiber-reinforced composite materials, highlighting their importance in advanced aerospace engineering systems.

Latest developments in materials science have enabled the integration of nanomaterials into polymer matrices to develop multifunctional composite systems capable of simultaneously providing structural reinforcement, electrical conductivity, and thermal stability (Gibson, 2010 [12]; Balasubramanian *et al*., 2016) [4]. In particular, graphene-based nanocomposites have gained growing attention for aerospace structures because of their ability to combine lightweight structural performance with enhanced electrical and thermal properties (Kausar *et al*., 2023) [14].

Carbon Fiber Composites

Carbon fiber reinforced polymer (CFRP) composite materials are broadly considered as one of the most prominent classes of lightweight structural materials used in aerospace engineering. These materials comprise high-strength carbon fibers dispersed in a polymer matrix, resulting in composites that exhibit exceptional mechanical performance while maintaining significantly lower density compared with traditional metallic materials (Luo, 2023) [20]. CFRPs provide high tensile strength, excellent stiffness, corrosion resistance, and outstanding fatigue performance, rendering them well suited for structural components, for instance aircraft fuselages, wings, and satellite structures (Sánchez *et al*., 2022) [29].

One of the notable advantages of CFRPs is their superior strength-to-weight ratio, facilitating the design of lightweight yet structurally robust components. Carbon fibers impart high tensile strength and rigidity, whereas the polymer matrix facilitates load distribution and protects the fibers from environmental damage. This synergistic interaction allows CFRPs to withstand complex mechanical stresses encountered in aerospace environments (Chukov *et al.*, 2019) [7]. Compared with conventional metallic materials, fiber-reinforced composites offer significantly improved strength-to-weight ratios and enhanced fatigue resistance, making them attractive for aerospace structural design (Soutis, 2005; Campbell, 2010) [6, 34].

Due to these properties, carbon fiber composites are also being explored for applications beyond aerospace, including lightweight automotive systems and energy-efficient vehicle design. Previous studies have shown that graphene-reinforced carbon fiber composites can significantly enhance structural efficiency and reduce overall material weight while improving multifunctional performance (Kumar *et al*., 2021; Dai *et al*., 2012) [10, 17].

Despite these advantages, conventional CFRP materials exhibit certain limitations, particularly in terms of electrical conductivity, impact resistance, and multifunctional performance. These limitations become increasingly significant in advanced aerospace systems where structural materials must also provide additional functionalities such as EMI shielding and thermal management. Consequently, researchers have explored nanomaterial reinforcements to enhance the multifunctional performance of CFRP composites (Yang *et al*., 2022) [40].

Graphene as Reinforcement

Graphene is a two-dimensional carbon nanomaterial consisting of a single atomic layer of carbon atoms arranged in a hexagonal lattice structure. It has gained significant attention because of its outstanding mechanical strength, electrical conductivity, and thermal properties. Since its isolation and characterization, graphene has been recognized as a revolutionary nanomaterial with remarkable physical properties, including extremely enhanced tensile strength, exceptional electrical conductivity, and improved thermal stability (Novoselov *et al*., 2004; Geim & Novoselov, 2007) [11, 23].

Graphene exhibits high resistance to tensile stress and exhibits remarkable electrical conductivity, making it one of the most promising nanomaterials for enhancing the performance of composite materials (Li, 2020) [5]. When incorporated into polymer matrices, graphene can substantially enhance mechanical strength, electrical conductivity, and thermal properties of the developed composite materials (Kim *et al*., 2010; Potts *et al*., 2011; Kuilla *et al*., 2010) [15, 16, 25].

Functionalized graphene sheets have also been shown to significantly enhance the mechanical stiffness and thermal conduction performance of polymer nanocomposites even at very low filler concentrations (Ramanathan *et al*., 2008 [28]). The incorporation of graphene nanosheets enhances the interfacial interaction between carbon fibers and the polymer matrix, resulting in more efficient load transfer and increased resistance to crack propagation within the composite structure. As a result, graphene-enhanced carbon fiber composites demonstrate improved tensile strength, fracture toughness, and impact resistance compared with conventional CFRP materials (Wu *et al*., 2014; Mirabedini *et al*., 2020) [21, 31].

Moreover, graphene contributes to the generation of continuous conductive pathways throughout the composite matrix, which enhances electrical conductivity and enables additional functionalities such as electromagnetic interference shielding and thermal management (Compton & Nguyen, 2010; Yang *et al*., 2022) [9, 40]. Advances in scalable fabrication techniques have further facilitated the large-scale production of graphene-based composite materials, improving their practical applicability in engineering systems. For instance, Park *et al*. (2023) [24] highlighted recent developments in scalable manufacturing approaches for graphene-based composites and emphasized their potential for integration into advanced structural and multifunctional materials.

Beyond mechanical reinforcement, recent studies have also investigated the multifunctional capabilities of graphene-enhanced carbon fiber composites, particularly in terms of improving electrical conductivity and thermal transport properties. For example, graphene interlayers incorporated within carbon-fiber/PEEK laminates have been shown to significantly enhance electrical conductivity and thermal diffusivity, demonstrating the potential of graphene-based modifications for multifunctional aerospace composite structures (Leow *et al*., 2023) [18].

These multifunctional capabilities make graphene-reinforced composites highly desirable for aerospace applications where both structural integrity and electronic protection are essential.

Importance of EMI Shielding

Modern aerospace platforms incorporate a wide range of electronic systems, including communication devices, radar systems, and navigation equipment. These components are highly sensitive to electromagnetic interference (EMI), which can disrupt signal transmission, degrade system performance, and potentially lead to critical system failures (Tong, 2016) [36]. Consequently, the development of materials capable of effectively shielding electromagnetic radiation has become increasingly important in aerospace and defence applications.

Electromagnetic interference occurs when unwanted electromagnetic radiation disturbs the normal functioning of electronic devices. Sources of EMI include radar systems, wireless communication networks, and other electronic equipment operating within the same electromagnetic environment. Such interference can result in signal distortion, malfunction of electronic systems, and degradation of communication reliability (Raagulan *et al*., 2020) [26].

Traditionally, metallic materials such as copper and aluminium have been extensively utilized for electromagnetic interference shielding due to their exceptional electrical conductivity and enhanced electromagnetic radiation reflectance (Chung, 2001; Tong, 2016) [8, 36]. However, these materials increase the overall weight of aerospace structures, which conflicts with the growing demand for lightweight engineering solutions. Consequently, research has increasingly focused on lightweight composite materials capable of providing both structural reinforcement and effective electromagnetic shielding.

Among advanced materials, graphene-based composites have gained significant attention because of their high electrical conductivity and their capability to establish conductive networks within polymer matrices (Mostafavi Yazdi *et al*., 2023; Hong *et al*., 2023) [13, 22]. Graphene-based films and nanocomposites have demonstrated excellent electromagnetic shielding effectiveness while maintaining flexibility and low density (Shen *et al*., 2014) [31]. Recent studies have further highlighted the potential of carbon-based nanocomposites for achieving high EMI shielding performance across a wide frequency range (Kumar *et al*., 2021) [17]. Furthermore, advanced graphene structures such as lightweight and superelastic graphene aerogels have shown promising shielding performance while maintaining low density (Zhang *et al*., 2024) [41]. The diverse multifunctional properties of graphene-based nanocomposites further support their potential for aerospace electromagnetic protection systems (Kausar *et al*., 2023) [14].

Research Gap

Despite significant progress in the development of graphene-enhanced composite materials, a comprehensive understanding of their combined structural and electromagnetic performance in aerospace applications remains limited. Existing studies have largely focused on improving individual properties such as mechanical strength, electrical conductivity, or electromagnetic interference shielding.

For example, graphene-based materials have demonstrated promising EMI shielding performance and electrical conductivity in lightweight composite systems (Hong *et al*., 2023; Zhang *et al*., 2024) [13, 41], while graphene-carbon fiber composites have shown potential for improving structural efficiency and reducing weight in transportation applications (Dai *et al*., 2012) [10].

However, many studies emphasize material synthesis or isolated property evaluation rather than providing an integrated assessment of both structural and electromagnetic performance. Although recent research has demonstrated significant progress in graphene-enhanced fiber-reinforced polymer composites (Mirabedini *et al*., 2020) [21] and multifunctional graphene-based aerospace materials (Kausar *et al*., 2023; Leow *et al*., 2023) [14, 18], systematic comparative analyses between graphene-enhanced composites and conventional carbon fiber reinforced polymers remain limited (Raagulan *et al*., 2020) [26].

Therefore, a comprehensive comparative evaluation of graphene-enhanced carbon fiber composites in terms of mechanical strength, impact resistance, and EMI shielding effectiveness is necessary to better understand their suitability for lightweight aerospace applications.

Objective of the Study

The present study is intended to conduct a comparative analysis of graphene-enhanced carbon fiber composites with conventional carbon fiber reinforced polymers and other lightweight materials used in aerospace applications. The study focuses on evaluating key performance parameters including mechanical strength, impact resistance, electrical conductivity, and EMI shielding effectiveness. By synthesizing findings from existing research, this paper aims to provide a comprehensive understanding of the multifunctional advantages of graphene-reinforced composites and their potential role in the development of advanced lightweight materials for next-generation aerospace applications.

Methodology

This study employs a literature-based comparative research methodology to systematically evaluate the structural and electromagnetic performance of graphene-enhanced carbon fiber composites. Since no experimental work was conducted, the analysis relies on secondary data obtained from previously published scientific studies. Literature-based research methods are widely used to synthesize existing knowledge, identify research trends, and develop comprehensive insights into emerging technological fields. Such approaches enable researchers to systematically analyze and integrate findings from multiple studies in order to generate meaningful comparisons and identify patterns across the literature (Snyder, 2019) [33].

The methodological framework applied in this study follows the principles of systematic literature review and comparative analysis, which involve structured literature identification, screening of relevant studies, and comparative evaluation of selected research findings. Systematic review methodologies improve the transparency, reliability, and reproducibility of research by ensuring that literature selection and analysis follow clearly defined procedures (Tranfield *et al*., 2003) [37].

The overall research process consisted of five major stages: defining the research design, identifying relevant data sources, applying study selection criteria, determining comparative performance parameters, and conducting cross-study analytical evaluation.

1. Research Design

The research design adopted in this study is based on a comparative literature analysis approach that systematically reviews previously published studies on graphene-reinforced carbon fiber composites. Comparative literature analysis allows researchers to evaluate variations in material performance reported across different studies, experimental conditions, and fabrication methods. This approach is particularly useful in advanced materials research, where numerous independent studies provide experimental data that can be synthesized to identify general performance trends (Snyder, 2019) [33]. This approach is particularly suitable for the present study, which aims to address the lack of integrated comparative evaluation of mechanical and electromagnetic performance in graphene-enhanced composite materials identified in the literature.

In this study, the comparative analysis focuses on evaluating how graphene incorporation influences key structural and electromagnetic properties of carbon fiber composites. By analyzing secondary data from multiple studies, the research aims to identify consistent improvements in mechanical strength, impact resistance, and electromagnetic interference shielding capabilities.

The research design follows a structured review methodology in which the literature is systematically collected, screened, and analyzed. Structured review frameworks enhance the credibility of literature-based research by ensuring that the review process remains transparent and replicable (Tranfield *et al*., 2003) [37].

2. Data Sources

The literature used in this study was obtained from major international scientific databases and digital libraries that provide access to peer-reviewed publications in materials science, nanotechnology, and aerospace engineering. These databases were selected because they contain high-quality academic research and offer comprehensive coverage of studies related to composite materials and nanotechnology.

The primary databases used for literature retrieval include: Scopus, Web of Science, ScienceDirect, IEEE Xplore, and SpringerLink.

Relevant studies were identified using combinations of keywords related to graphene composites and electromagnetic shielding materials. Example search terms included: *graphene reinforced carbon fiber composites, graphene polymer nanocomposites, electromagnetic interference shielding composites, lightweight aerospace composite materials, graphene conductive composites*.

The use of multiple academic databases improves the comprehensiveness of literature retrieval and reduces the likelihood of omitting relevant studies. Systematic literature searches across multiple databases are recommended in structured review methodologies to ensure broad coverage of relevant research publications (Tranfield *et al*., 2003) [37].

3. Study Selection Criteria

A set of inclusion criteria was established during the literature screening stage to ensure the relevance and reliability of the selected studies. These criteria helped identify studies that were directly relevant to the objectives of the current investigation.

The criteria outlined below were applied when selecting studies for comparative analysis:

1. Publication Period: Studies published between 2015 and 2025 were prioritized in order to capture recent developments in graphene-based composite materials.

2. Material Focus: The selected studies must investigate graphene-reinforced carbon fiber composites or graphene-based polymer composites used for structural reinforcement or electromagnetic shielding applications.

3. Performance Evaluation: The selected studies must report quantitative or qualitative evaluation of at least one of the material properties such as mechanical strength, impact resistance, electrical conductivity or electromagnetic interference shielding effectiveness

4. Publication Quality: Only peer-reviewed journal articles, conference proceedings, and scholarly review papers were included to ensure academic reliability.

Studies that did not focus on graphene-based composite materials or did not report relevant performance characteristics were excluded from the analysis. The application of defined inclusion and exclusion criteria is an important component of systematic literature review methodologies because it improves the transparency and replicability of the research methodology (Tranfield *et al*., 2003; Snyder, 2019) [33, 37].

4. Comparative Parameters

The comparative evaluation in this study focuses on key material performance parameters that determine the suitability of graphene-enhanced carbon fiber composites for aerospace applications. These parameters were selected based on their importance in determining structural performance, durability, and electromagnetic compatibility in advanced engineering systems.

The following parameters were used as the basis for comparative analysis:

1. Tensile Strength: Tensile strength refers to the capacity of a composite material to resist axial mechanical loading without experiencing structural failure. It is a critical parameter for aerospace structures where materials are subjected to high mechanical stresses.

2. Impact Resistance: Impact resistance represents the ability of a composite material to absorb and dissipate energy under sudden or dynamic mechanical loading conditions. This property is essential for ensuring structural durability and damage tolerance in aerospace components.

3. Electrical Conductivity: Electrical conductivity determines the ability of the composite material to conduct electrical current. This property is particularly important for graphene-based composites because conductive networks formed by graphene nanosheets influence electromagnetic shielding performance.

4. EMI Shielding Effectiveness: Electromagnetic interference shielding effectiveness (EMI SE) measures the ability of a material to reduce the intensity of electromagnetic radiation. This property is critical for protecting sensitive electronic systems in aerospace and defence platforms.

5. Weight Efficiency: Weight efficiency refers to the balance between mechanical performance and material density. Lightweight materials that maintain high structural strength are particularly desirable in aerospace engineering because they contribute to improved fuel efficiency and system performance.

These parameters provide a comprehensive framework for evaluating the multifunctional performance of graphene-enhanced carbon fiber composites.

Analytical Approach

The selected studies were analyzed using a **structured comparative analytical framework** that integrates cross-study comparison, trend analysis, and performance benchmarking as follows:

1. Cross-Study Comparison: Cross-study comparison was used to evaluate differences in reported material properties across multiple studies. By comparing results obtained under different fabrication techniques, graphene concentrations, and composite configurations, the analysis identifies variations in composite performance reported in the literature.

2. Trend Analysis: Trend analysis was applied to identify general patterns in the reported effects of graphene reinforcement on composite properties. By synthesizing findings across multiple studies, it becomes possible to determine whether graphene incorporation consistently improves structural and electromagnetic performance.

3. Performance Benchmarking: Performance benchmarking was conducted by comparing graphene-enhanced carbon fiber composites with conventional composite materials reported in the literature. This comparison helps evaluate the relative advantages of graphene-based composites in terms of mechanical strength, electromagnetic shielding capability, and weight efficiency.

The use of structured analytical methods improves the rigor and clarity of literature-based research by ensuring that the analysis remains systematic and transparent (Snyder, 2019) [33].

Result and Discussion

1. Graphene-Enhanced Carbon Fiber Composites

1.1 Structure and Composition

Graphene-enhanced carbon fiber composites represent a class of multifunctional materials in which graphene nanostructures are incorporated within a carbon fiber reinforced polymer (CFRP) matrix to improve both structural and electromagnetic properties. In conventional CFRP systems, carbon fibers serve as the primary load-bearing component, while the polymer matrix facilitates stress distribution and provides protection to the fibers against environmental degradation. The incorporation of graphene nanoplatelets or nanosheets within the polymer matrix introduces nanoscale reinforcement that enhances the adhesion at the fiber-matrix interface.

The structural configuration of graphene-reinforced composites is illustrated in Fig 1, where graphene nanosheets are dispersed within the polymer matrix and around carbon fibers. This dispersion enhances mechanical interlocking between the reinforcing fibers and the surrounding matrix and contributes to improved electrical conductivity by establishing interconnected conductive networks within the material. The high surface area and two-dimensional structure of graphene nanosheets enable strong interfacial interactions with the surrounding matrix, thereby improving stress transfer efficiency and resistance to crack propagation within the composite material. Similar structural reinforcement mechanisms have been documented in graphene-enhanced fiber-reinforced polymer composites, in which the integration of graphene nanomaterials significantly improves both structural and functional properties of the composite materials (Stankovich *et al*., 2006; Mirabedini *et al*., 2020) [21, 35].

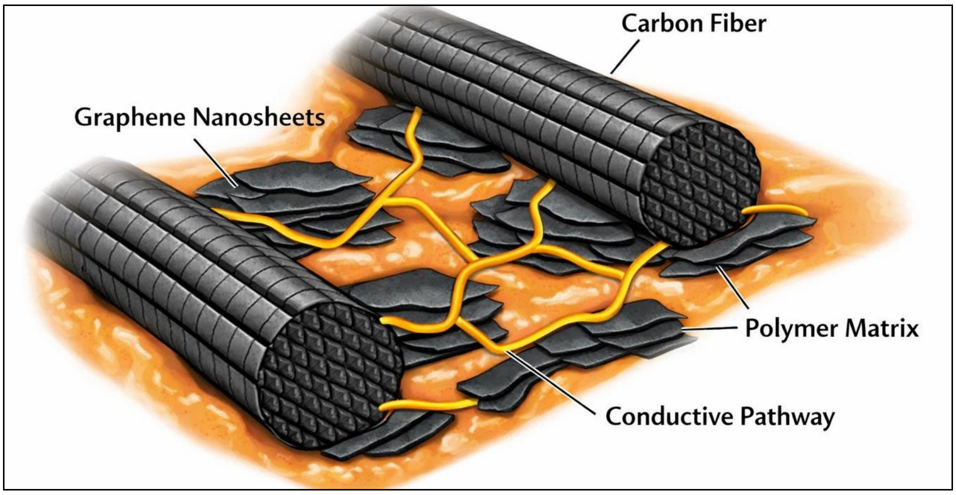

Fig 1: Graphene-Carbon Fiber Composite Structure.

Structural schematic of graphene-enhanced carbon fiber reinforced polymer (CFRP) composites depicting the distribution of graphene nanosheets within the polymer matrix surrounding the reinforcing carbon fibers. The incorporation of graphene improves fiber-matrix interfacial bonding, enhances stress transfer efficiency, and forms conductive pathways that contribute to improved mechanical performance and electrical conductivity of the composite material (adapted from Stankovich *et al*., 2006) [35].

The structural arrangement illustrated in Fig 1 highlights the role of graphene nanosheets in reinforcing the fiber–matrix interface within carbon fiber composites. The presence of graphene layers increases the effective contact area between the polymer matrix and carbon fibers, enabling improved load transfer and crack resistance. In addition, the generation of conductive pathways throughout the matrix facilitates improved electrical conductivity, which is essential for electromagnetic shielding applications in aerospace systems (Stankovich *et al*., 2006; Mirabedini *et al*., 2020 [21, 35]).

1.2 Manufacturing Techniques

Several fabrication techniques have been developed to incorporate graphene nanomaterials into carbon fiber composites. Among these methods, Resin Transfer Molding (RTM) and Vacuum Assisted Resin Infusion (VARI) are broadly employed in the production of graphene-modified CFRP components. In RTM processes, graphene nanoparticles are dispersed within liquid resin and injected into molds containing carbon fiber preforms, allowing uniform impregnation of fibers and improved graphene dispersion within the polymer matrix.

Similarly, VARI processes utilize vacuum pressure to draw graphene-modified resin into carbon fiber fabrics, producing composites with improved matrix infiltration and reduced void formation. Another emerging approach involves Chemical Vapor Deposition (CVD) techniques, which allow graphene layers to be deposited directly onto carbon fiber surfaces to enhance electrical conductivity and interfacial bonding.

Recent studies have also explored scalable manufacturing approaches for integrating graphene into CFRP structures. For instance, graphene can be introduced into interlaminar regions of composites through spray deposition or interlayer modification techniques, enabling improvements in electrical and thermal conductivity without significantly altering conventional composite manufacturing processes (Leow *et al*., 2023) [18]. Such approaches demonstrate the potential for scalable production of multifunctional graphene-enhanced composites for aerospace applications.

2. Comparative Analysis of Mechanical Properties

Previous studies have demonstrated that incorporating graphene nanomaterials into carbon fiber composites can significantly enhance mechanical properties such as tensile strength, impact resistance, and fatigue durability. These improvements are attributed to nanoscale reinforcement mechanisms introduced by graphene within the polymer matrix.

2.1 Tensile Strength

Tensile strength is a critical mechanical parameter for aerospace structural materials. Conventional CFRP composites already exhibit high tensile strength due to the load-bearing capacity of carbon fibers. However, graphene nanosheets can further enhance this property by strengthening the fiber-matrix interface and improving stress transfer efficiency.

As summarized in Table 1, numerous studies have reported significant improvements in tensile strength after the incorporation of graphene into polymer or CFRP matrices. Graphene–polymer composites have demonstrated tensile strength improvements of approximately 20–40%, while graphene–epoxy composites have reported increases of up to 50%, depending on graphene concentration (Kuilla *et al*., 2010; Stankovich *et al*., 2006 [16, 35]).

These improvements are largely ascribed to strengthened interfacial interactions and the ability of graphene nanosheets to reinforce the polymer matrix at the nanoscale.

In addition, graphene incorporation has been shown to augment electrical and thermal conductivity of carbon fiber composites while maintaining mechanical integrity, thereby enabling multifunctional composite structures suitable for aerospace systems (Leow *et al*., 2023 [18]).

2.2 Impact Resistance

Impact resistance represents another important property for aerospace structures that are subjected to dynamic loading and potential impact events. The addition of graphene nanosheets improves impact resistance through mechanisms such as crack deflection, crack bridging, and energy dissipation during fracture processes.

Graphene nanoplatelets act as effective crack arresters, preventing the propagation of micro-cracks within the composite matrix. As summarized in Table 1, several studies have reported improved fracture toughness and impact resistance in graphene-reinforced composites due to enhanced interfacial bonding and nanoscale reinforcement effects (Rafiee *et al*., 2009 [27]; Wu *et al*., 2014).

Table 1: Mechanical improvements in graphene-enhanced carbon fiber composites compared with conventional *carbon fiber reinforced polymer (*CFRP) materials reported in literature

Composite System	Graphene Content	Tensile Strength Improvement	Impact Resistance Improvement	Key Observation	Reference
Graphene–polymer composite	~0.1–1 wt%	~20–40% increase	Improved fracture resistance	Graphene improves stress transfer within the polymer matrix and enhances stiffness	Stankovich *et al*. (2006) [35]
Graphene–epoxy composite	<1 wt%	~25–50% increase	Significant improvement	Uniform dispersion of graphene improves fiber–matrix interfacial bonding	Kuilla *et al*. (2010) [16]
Graphene nanoplatelet reinforced CFRP	~0.5 wt%	~30% increase	Higher crack resistance	Graphene nanoplatelets act as crack arresters and enhance load transfer	Wu *et al*. (2014)
Graphene oxide–epoxy nanocomposite	~0.1 wt%	~30–40% increase	Improved fracture toughness	Graphene oxide improves mechanical reinforcement at low filler loading	Rafiee *et al*. (2009) [27]
Graphene-coated carbon fiber composite	Thin graphene layer	~35–45% increase	Improved fatigue resistance	Graphene coating strengthens fiber–matrix interface and delays crack propagation	Yang *et al*. (2022) [40]
Graphene aerogel composite structure	Nanostructured graphene	Enhanced structural stability	High energy absorption	Lightweight graphene architecture improves mechanical resilience	Zhang *et al*. (2024) [41]

The studies summarized in Table 1 demonstrate a consistent trend in which the incorporation of graphene nanosheets improves mechanical performance of fiber-reinforced composites. Tensile strength improvements ranging from approximately 20–50% have been reported depending on graphene content and dispersion quality. These improvements predominantly arise from enhanced interfacial bonding, improved stress transfer efficiency, and crack-bridging mechanisms introduced by graphene reinforcement (Kuilla *et al*., 2010; Rafiee *et al*., 2009) [16, 27]. Additionally, graphene-modified composites exhibit improved durability and fatigue resistance due to reduced crack propagation within the composite matrix (Mirabedini *et al*., 2020) [21].

2.3 Fatigue Resistance

Fatigue resistance is of critical importance for aerospace materials undergoing repeated cyclic loading during service. Graphene reinforcement contributes to improved fatigue performance by strengthening the fiber-matrix interface and delaying crack initiation under cyclic stress conditions.

Graphene-modified fiber-reinforced polymer composites have demonstrated improved durability and structural stability due to improved load distribution and reduced crack propagation within the composite structure (Mirabedini *et al*., 2020 [21]).

Overall, the grapheme reinforcement- related mechanical improvements are illustrated in Fig 2, which compares the performance of conventional CFRP and graphene-enhanced CFRP composites. The chart demonstrates that graphene-reinforced composites consistently outperform conventional CFRP in tensile strength, impact resistance, and EMI shielding performance.

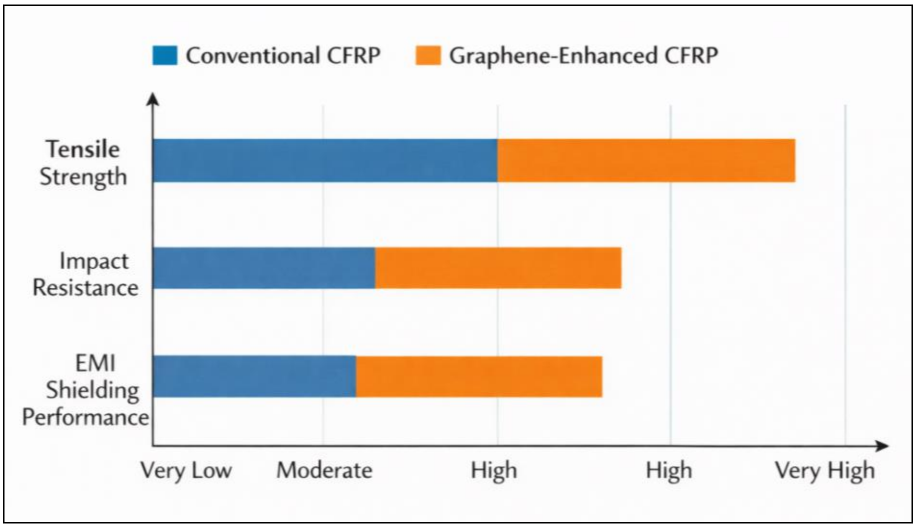

Fig 2: Performance Comparison Chart

Comparative performance of conventional carbon fiber reinforced polymer (CFRP) composites and graphene-enhanced CFRP composites in terms of tensile strength, impact resistance, and electromagnetic interference (EMI) shielding efficacy. The incorporation of graphene nanosheets improves mechanical reinforcement and electrical conductivity within the composite matrix, leading to enhanced multifunctional performance (compiled from Kuilla *et al*., 2010; Kumar *et al*., 2021) [16, 17].

The comparative performance illustrated in Fig 2 indicates that graphene-enhanced CFRP composites outperform conventional CFRP in multiple performance categories. In particular, improvements in tensile strength and impact resistance result from improved fiber-matrix interfacial adhesion and more efficient stress transfer mechanisms. Furthermore, the electrical conductivity introduced by graphene nanosheets enables improved electromagnetic shielding performance, demonstrating the multifunctional advantages of graphene-reinforced composites (Leow *et al*., 2023; Kumar *et al*., 2021 [17, 18]).

3. Comparative Analysis of EMI Shielding

3.1 EMI Shielding Mechanism

In composite materials, electromagnetic interference (EMI) shielding is achieved through three primary mechanisms: reflection, absorption, and multiple internal scattering of electromagnetic radiation. These mechanisms are illustrated in Fig 3, which shows how electromagnetic waves interact with conductive filler networks within graphene-based composite materials.

Reflection takes place when incident electromagnetic waves strike a conductive surface and are redirected because of the impedance difference between the shielding material and its surrounding medium. In conductive polymer composites, the formation of interconnected conductive filler networks plays a critical role in enhancing EMI shielding through reflection and absorption mechanisms (Al-Saleh & Sundararaj, 2009; Kumar *et al*., 2021) [2, 17]. The absorption mechanism takes place when electromagnetic waves enter the material and lose energy through dielectric loss mechanisms or resistive heating within conductive pathways. Multiple internal scattering arises when electromagnetic waves are repeatedly reflected within the internal structure of the composite, resulting in further attenuation.

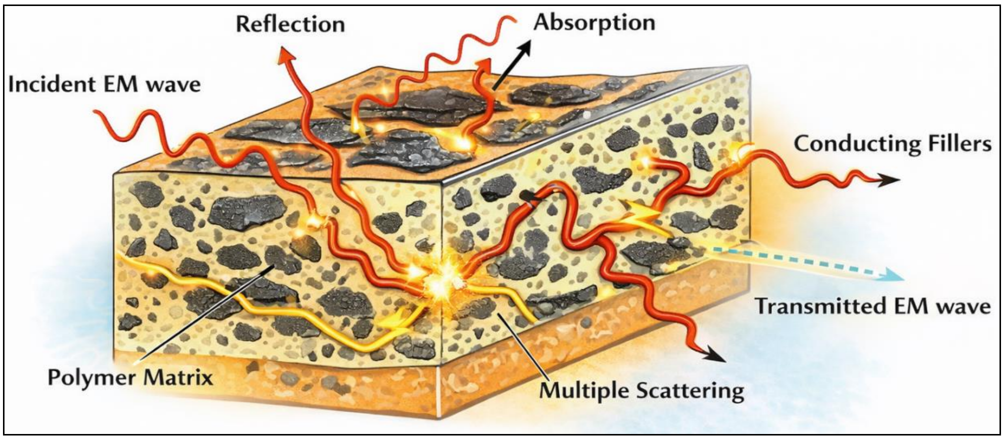

Fig 3: EMI Shielding Mechanism.

Schematic diagram illustrating EMI shielding mechanisms in graphene-based composites, including reflection, absorption, and repeated internal scattering of electromagnetic waves within conductive graphene networks embedded in a polymer matrix. These mechanisms together facilitate attenuation of incident electromagnetic radiation and improved shielding effectiveness (adapted from Kumar *et al*., 2021) [17].

Graphene nanosheets significantly enhance these mechanisms due to their high charge transport capability and layered two-dimensional architecture. When dispersed within polymer matrices, graphene forms interconnected conductive networks that improve the competence of the composite material to suppress electromagnetic radiation (Kumar *et al*., 2021) [17].

3.2 Graphene Contribution to EMI Shielding

The conductive networks formed by graphene nanoplatelets increase the electrical conduction properties of the composite material and enhance both reflection and absorption shielding mechanisms. Additionally, the large surface area of graphene promotes multiple internal reflections within the composite structure, further increasing shielding effectiveness.

Graphene-based nanocomposites have been extensively investigated for aerospace systems because they provide a combination of lightweight structural performance and multifunctional characteristics including electrical conductivity, thermal stability, and electromagnetic shielding capability (Kausar *et al*., 2023) [14].

3.3 Performance Comparison

Graphene-based composite materials have demonstrated shielding effectiveness values ranging from approximately 30 dB to more than 50 dB across different frequency ranges, particularly in lightweight composite systems containing conductive nanofillers (Singh *et al*., 2018; Shen *et al*., 2014; Hong *et al*., 2023) [13, 31, 32]. Similarly, lightweight graphene aerogel structures have demonstrated shielding effectiveness exceeding 50 dB while maintaining low density (Zhang *et al*., 2024 [41]). A comparison of EMI shielding performance reported for graphene-based composite materials in previous studies is summarized in Table 2.

Table 2. Reported electromagnetic interference (EMI) shielding performance of graphene-based and carbon-based composite materials.

Material	Frequency Range	EMI Shielding Effectiveness (SE)	Key Observation	Reference
Graphene thin film	GHz range	~30–40 dB	Thin graphene layers provide efficient EMI shielding with high electrical conductivity	Shen *et al*. (2014) [31]
Graphene/polymer nanocomposite	X-band	~30–45 dB	Conductive graphene networks improve shielding via reflection and absorption mechanisms	Yang *et al*. (2005) [39]
Conductive polymer composite with graphene fillers	Broadband	~40–60 dB	Conductive filler networks significantly enhance electromagnetic wave attenuation	Hong *et al*. (2023) [13]
Carbon-based nanocomposite	Microwave range	~20–50 dB	Carbon nanostructures enhance both reflection and absorption shielding mechanisms	Kumar *et al*. (2021) [17]
Graphene aerogel composite	GHz range	>50 dB	Lightweight porous graphene structures provide high shielding effectiveness	Zhang *et al*. (2024) [41]
Graphene paper / layered graphene film	GHz range	~40 dB	Layered graphene structures increase multiple internal reflections of EM waves	Shen *et al*. (2014) [31]

The EMI shielding values summarized in Table 2 indicate that graphene-based composites can achieve shielding effectiveness exceeding 30–50 dB depending on the composite structure and filler loading. The superior operational efficacy of these materials is largely linked to the formation of conductive graphene networks that enhance both reflection and absorption mechanisms. Additionally, the layered structure of graphene promotes multiple internal reflections within the composite matrix, further increasing shielding effectiveness (Shen *et al*., 2014; Kumar *et al*., 2021) [17, 31]. These attributes make graphene-reinforced composites attractive alternatives to traditional metallic shielding materials, particularly in lightweight aerospace applications (Kausar *et al*., 2023) [14].

These findings indicate that graphene-reinforced composites provide a promising balance between high electromagnetic shielding performance and lightweight structural characteristics.

3.4 Aerospace Application Potential

The multifunctional characteristics of graphene-enhanced carbon fiber composites make them viable candidates for diverse aerospace applications. Their combination of high mechanical strength, lightweight properties, and EMI shielding capability enables their integration into next-generation aerospace systems.

Graphene-based nanocomposites have been investigated for aerospace structures due to their ability to improve mechanical durability, electrical conductivity, thermal stability, and structural integrity while maintaining low material density (Kausar *et al*., 2023) [14]. These characteristics make graphene-enhanced composites particularly suitable for advanced aerospace structures where both structural and functional performance is required.

One potential application is in aircraft fuselage panels, where graphene-reinforced composites can provide structural reinforcement while simultaneously protecting onboard electronic systems from electromagnetic interference. Similarly, unmanned aerial vehicle (UAV) structures can benefit from the lightweight yet mechanically robust properties of graphene-enhanced composites, improving flight efficiency and operational endurance.

Another important application is in satellite enclosures and electronic housings, where electromagnetic shielding is essential for protecting communication and navigation equipment from interference. Graphene-based composite materials provide effective shielding without significantly increasing structural weight.

In addition, these materials can be applied in radar shielding systems and electromagnetic protection structures used in defence and aerospace applications. The combination of lightweight structural performance and advanced EMI shielding capability makes graphene-reinforced carbon fiber composites highly attractive for the design and development of cutting-edge aerospace materials.

Conclusion

This study presents a comparative literature-based evaluation of graphene-enhanced carbon fiber reinforced polymer (CFRP) composites with respect to their structural and electromagnetic performance for aerospace applications. The analysis synthesized findings from previously published studies to assess the effects of graphene incorporation on key material properties including tensile strength, impact resistance, electrical conductivity, and electromagnetic interference (EMI) shielding performance.

The comparative analysis indicates that graphene reinforcement significantly improves the mechanical performance of carbon fiber composites. Graphene nanosheets enhance fiber–matrix interfacial bonding, facilitate improved stress transfer, and act as effective crack-arrest mechanisms within the composite structure. As a result, graphene-enhanced composites demonstrate improved tensile strength, fracture toughness, and impact resistance compared with conventional CFRP materials.

Besides improving mechanical properties, the addition of graphene promotes the formation of conductive networks within the composite matrix, which increases electrical conductivity and improves EMI shielding performance. Literature reports indicate that graphene-based composite materials can achieve shielding effectiveness exceeding 30–50 dB while maintaining lightweight structural characteristics.

Overall, graphene-enhanced CFRP composites offer significant potential for next-generation aerospace materials that require both structural strength and electromagnetic protection. Future research should focus on hybrid nanocomposite systems combining graphene with other nanomaterials, the development of scalable manufacturing techniques, and the integration of smart sensing capabilities within multifunctional composite structures.

References

1. Adeleke AA, Agboola O, Sadiku ER, Daramola OO, Olubambi PA. Recent advances in polymer matrix composites for aerospace applications: a review. Composites Part B: Engineering,2024:259:110762. https://doi.org/10.1016/j.compositesb.2023.110762
2. Al-Saleh MH, Sundararaj U. Electromagnetic interference shielding mechanisms of CNT/polymer composites. Carbon,2009:47:1738-1746. https://doi.org/10.1016/j.carbon.2009.02.030
3. Baker A, Dutton S, Kelly D. Composite materials for aircraft structures. American Institute of Aeronautics and Astronautics, 2004.
4. Balasubramanian K, Burghard M, Kern K. Graphene-based materials for multifunctional composite applications. Progress in Materials Science,2016:83:76-134. https://doi.org/10.1016/j.pmatsci.2016.02.003
5. Bhavya ML, Ramesh M, Babu KS. Recent developments in polymer composites for aerospace applications. Materials Today: Proceedings,2020:22:281-287. https://doi.org/10.1016/j.matpr.2019.08.146
6. Campbell FC. Structural composite materials. ASM International, 2010.
7. Chukov DI, Stepashkin AA, Senatov FS, Kaloshkin SD. Mechanical properties of carbon fiber reinforced polymer composites: a review. Composites Part B: Engineering,2019:173:106928. https://doi.org/10.1016/j.compositesb.2019.106928
8. Chung DDL. Electromagnetic interference shielding effectiveness of carbon materials. Carbon,2001:39:279-285. https://doi.org/10.1016/S0008-6223(00)00184-6
9. Compton OC, Nguyen ST. Graphene oxide, highly reduced graphene oxide, and graphene: versatile building blocks for carbon-based materials. Small,2010:6:711-723. https://doi.org/10.1002/smll.200901934
10. Dai L, Chang DW, Baek JB, Lu W. Carbon nanomaterials for advanced energy conversion and storage. Small,2012:8:1130-1166. https://doi.org/10.1002/smll.201101594
11. Geim AK, Novoselov KS. The rise of graphene. Nature Materials,2007:6:183-191. https://doi.org/10.1038/nmat1849
12. Gibson RF. A review of recent research on mechanics of multifunctional composite materials and structures. Composite Structures,2010:92:2793-2810. https://doi.org/10.1016/j.compstruct.2010.05.003
13. Hong J, Kwon J, Im D, Ko J, Nam CY, Yang HG, *et al.* Best practices for correlating electrical conductivity with broadband EMI shielding in binary filler-based conducting polymer composites. Chemical Engineering Journal,2023:455:140528. https://doi.org/10.1016/j.cej.2022.140528
14. Kausar A, Ahmad I, Eisa MH, Maaza M. Graphene nanocomposites in space sector—fundamentals and advancements. C,2023:9:29. https://doi.org/10.3390/c9010029
15. Kim H, Abdala AA, Macosko CW. Graphene/polymer nanocomposites. Macromolecules,2010:43:6515-6530. https://doi.org/10.1021/ma100572e
16. Kuilla T, Bhadra S, Yao D, Kim NH, Bose S, Lee JH. Recent advances in graphene based polymer composites. Progress in Polymer Science,2010:35:1350-1375. https://doi.org/10.1016/j.progpolymsci.2010.07.005
17. Kumar R, Sahoo S, Joanni E, Singh RK, Tan WK, Kar KK, Matsuda A. Recent progress on carbon-based composite materials for microwave electromagnetic interference shielding. Carbon,2021:177:304-331. https://doi.org/10.1016/j.carbon.2021.01.107
18. Leow C, Kreider PB, Sommacal S, Kluth P, Compston P. Electrical and thermal conductivity in graphene-enhanced carbon-fibre/PEEK: the effect of interlayer loading. Carbon,2023:215:118463. https://doi.org/10.1016/j.carbon.2023.118463
19. Li X. Graphene-based nanomaterials and their composites: a review of synthesis and applications. Materials Science and Engineering R: Reports,2020:142:100578. https://doi.org/10.1016/j.mser.2020.100578
20. Luo X. Advances in carbon fiber reinforced polymer composites for aerospace structural applications. Composite Structures,2023:315:116993. https://doi.org/10.1016/j.compstruct.2023.116993
21. Mirabedini A, Ang A, Nikzad M, Fox B, Lau KT, Hameed N. Evolving strategies for producing multiscale graphene-enhanced fiber-reinforced polymer composites for smart structural applications. Advanced

Science,2020:7:1903501. https://doi.org/10.1002/advs.201903501
22. Mostafavi Yazdi S, Mahdavian M, Karimi M. Lightweight graphene-based nanocomposites for electromagnetic interference shielding applications: a review. Journal of Materials Science,2023:58:14001-14028. https://doi.org/10.1007/s10853-023-08469-3
23. Novoselov KS, Geim AK, Morozov SV, Jiang D, Zhang Y, Dubonos SV, Grigorieva IV, Firsov AA. Electric field effect in atomically thin carbon films. Science,2004:306:666-669. https://doi.org/10.1126/science.1102896
24. Park S, Lee H, Kim S. Recent developments in scalable fabrication techniques for graphene-based composite materials: challenges and opportunities. Advanced Materials,2023:32:2206412. https://doi.org/10.1002/adma.202206412
25. Potts JR, Dreyer DR, Bielawski CW, Ruoff RS. Graphene-based polymer nanocomposites. Polymer,2011:52:5-25. https://doi.org/10.1016/j.polymer.2010.11.042
26. Raagulan K, Kim D, Choi J, Lee H, Kim H. Electromagnetic interference shielding effectiveness of graphene-based composite materials. Composites Part B: Engineering,2020:200:108344. https://doi.org/10.1016/j.compositesb.2020.108344
27. Rafiee MA, Rafiee J, Wang Z, Song H, Yu ZZ, Koratkar N. Enhanced mechanical properties of nanocomposites at low graphene content. ACS Nano,2009:3:3884-3890. https://doi.org/10.1021/nn9010472
28. Ramanathan T, Abdala AA, Stankovich S, Dikin DA, Herrera-Alonso M, Piner RD, Adamson DH, Schniepp HC, Chen X, Ruoff RS, Nguyen ST, Brinson LC. Functionalized graphene sheets for polymer nanocomposites. Nature Nanotechnology,2008:3:327-331. https://doi.org/10.1038/nnano.2008.96
29. Sánchez M, Molina S, Martínez A. Mechanical performance of carbon fiber reinforced polymer composites for aerospace structures. Composite Structures,2022:286:115283. https://doi.org/10.1016/j.compstruct.2022.115283
30. Schutz RW, Grauman JS. Corrosion resistance of aerospace alloys. Corrosion,1986:42:130-140. https://doi.org/10.5006/1.3584903
31. Shen B, Zhai W, Zheng W. Ultrathin flexible graphene film: an excellent thermal conducting material with efficient electromagnetic interference shielding. Advanced Functional Materials,2014:24:4542-4548. https://doi.org/10.1002/adfm.201400079
32. Singh AK, Shishkin A, Koppel T, Gupta N. A review of porous lightweight composite materials for electromagnetic interference shielding. Composites Part B: Engineering,2018:149:188-197. https://doi.org/10.1016/j.compositesb.2018.05.036
33. Snyder H. Literature review as a research methodology: an overview and guidelines. Journal of Business Research,2019:104:333-339. https://doi.org/10.1016/j.jbusres.2019.07.039
34. Soutis C. Fibre reinforced composites in aircraft construction. Progress in Aerospace Sciences,2005:41:143-151. https://doi.org/10.1016/j.paerosci.2005.02.004
35. Stankovich S, Dikin DA, Dommett GH, Kohlhaas KM, Zimney EJ, Stach EA, Piner RD, Nguyen ST, Ruoff RS. Graphene-based composite materials. Nature,2006:442:282-286. https://doi.org/10.1038/nature04969
36. Tong XC. Advanced materials for electromagnetic shielding: fundamentals, properties, and applications. Wiley, 2016.
37. Tranfield D, Denyer D, Smart P. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. British Journal of Management,2003:14:207-222. https://doi.org/10.1111/1467-8551.00375
38. Wu F, Sun M, Wang M. Graphene-based composite materials for electromagnetic interference shielding. Chinese Science Bulletin,2014:59:1681-1687. https://doi.org/10.1360/972013-1045
39. Yang Y, Gupta MC, Dudley KL, Lawrence RW. Conductive carbon nanofiber–polymer foam structures. Advanced Materials,2005:17:1999-2003. https://doi.org/10.1002/adma.200500467
40. Yang Y, Wan C, Huang Q, Hua J. Pore-rich cellulose-derived carbon fiber@graphene core-shell composites for electromagnetic interference shielding. Nanomaterials,2022:13:174.
41. Zhang Y, Min P, Yue G, Niu B, Li L, Yu ZZ, Zhang HB. Emulsion-based multiscale structural design realizes lightweight and superelastic graphene aerogels for electromagnetic interference shielding. Small,2024:20:NA. https://doi.org/10.1002/smll.202405950