Mechanistic Approach Towards Structural Design of Aramid-CNT Composites: Bulk Performance Optimization, Multiscale Reinforcement, and Interphase Engineering

Pranali Dhiware*

The Bombay Textile Research Association, LBS Marg, Ghatkopar (W), Mumbai 40086, India.

Abstract

High-performance composites development has been focused on enhancing the fiber strength, specific modulus, matrix rigidity, and lightweight frameworks. Aramid Fibers (such as Kevlar, Twaron, and Nomex), being high-performance fibers, have garnered lot of attention as a reinforcing material in polymer composites due to their remarkable properties, including low density and high temperature endurance. Nevertheless, their smooth and chemically inactive surfaces naturally limit matrix adherence and overall structural performance. Researchers have been exploring numerous reinforcements to overcome these issues, and CNTs have surfaced as a viable option for addressing the existing challenges through multiscale bridging, hierarchical structural design, and interphase engineering. Lightweight profiles and superior mechanical strength together have led to their distinct thermal and electrical properties. The structural and mechanical behavior of aramid-CNT composites have been critically assessed in the present work by studying their molecular interactions and optimization routes. Moreover, interlayer designs, functionalizations, dispersion methods, and performance evaluation metrics have also been explored, thereby providing an insight into both present technical hurdles and future development objectives.

Key words:

High-performance composites, CNTs, aramid fibers, multiscale reinforcements, interphase engineering

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1.0 Introduction

1.1. Background of Structural Composites

Composite materials have become crucial in modern engineering and architectural frameworks since they combine a load carrying reinforcement with high specific strength and modulus, resistance to corrosion, and enhanced multifunctional properties unattainable with traditional monolithic components [1, 2, 3]. The term 'Composites' has been constituted by two different elements, mainly the matrix and reinforcement [4]. A coherent framework has been produced across all the geometric dimensions as the matrix shapes the overall configurations and the reinforcement [1, 2]. Polymer fiber-reinforced composites have become paramount in various domains, such as marine, defenses, automotive and renewable energy, due to their enhanced strength-to-weight proportions, facilitating structural changes tailored for particular load-bearing requirements [5, 6]. A wide variety of composite fibers such as carbon fiber composites, dominate stiffness-related applications, glass fibers offer cost-efficient large-scale solutions, whereas, aramid fibers have a unique role when toughness, thermal stability, and impact resistance all have been demanded collectively [7]. The future structural durability of composites have been still largely dependent on the interfacial mechanics despite the advancements in constituent materials as interphase failure, cracking and delamination often controls final structural breakdown [8, 9].

To address the gaps in conventional macro-fiber design, Nepal et. al. highlighted the hierarchical reinforcement emerging as a potential next-generation structural composite over single-scale strengthening, displaying the possibility of nanoscale reinforcements. Their results showed that the optimization of composites required the simultaneous control of the constituent materials, multiscale load transfer channels and the interface structure [10].

*Corresponding author,

E-mail: pranalidhiware@gmail.com

1.2. Aramid Fibers in Structural Applications

Aramid fibers are a class of aromatic polyamide fiber with the characteristics of strong and rigid molecular structure [11]. Their robust hydrogen bonding and high crystallinity provide remarkable properties contributing to the outstanding tensile strength, specific modulus, impact resistance, and thermal stability [12]. Commercial-graded aramids such as Nomex, Kevlar, and Twaron have become essential reinforcements in marine systems, ballistic armour, pressure vessels involving tolerance to damage and lightweight designs, and aerospace structures [13]. Their capability to absorb and emit significant amount of energy through the fibrillation process have made them exceptional [14, 15]. Also, by combining mechanical performance with toughness and longevity under dynamic loading circumstances, they have a unique role among the reinforcement composites [16]. Despite their advantages, aramid composites often perform below the theoretical expectations due to the failure to effectively translate intrinsic fiber properties to bulk structural performance [17]. Low interfacial friction and poor matrix adhesion have limited the load transfer efficiency resulting in premature debonding, delamination, and resistance to durability [18, 19].

Although aramid fibers display outstanding dynamic toughness, their composite performance is often compromised by poor matrix coupling as noted by Patterson et. al. who emphasized the significance of surface engineering and nanoscale reinforcement strategies [20].

1.3. Limitations in Bulk Mechanical Performance

Aramid fibers exhibit remarkable tensile properties at a molecular level, which do not always fully translate to the superior performance in bulk composites, largely because their interaction among the fiber-matrix interface shows effectiveness, often more than the pristine fibers themselves [21, 22]. Para-aramid fibers like Kevlar usually possess tensile strength of approximately 2.9-3.8 GPa and moduli around 70-135 GPa [23]. Despite this, the reinforced composites of aramid fibers sometimes show interlaminar performance and compressive strength below the desirable range, which can be attributed to inefficient stress transfer across the interface [24]. These drawbacks result in the fiber pull-out, fracture propagation, delamination, and decreased structural durability leading to limitations in IFSS due to inefficient load transfer between reinforcement and the matrix [25].

The situation becomes more complex, when the stress concentrations escalate in weak interphase regions under complicated loading conditions like fatigue, compression, impact, and ballistic events [21]. While the aramid fibers become prone to kink-band and microbuckling development under compressive strength, they result in the compressive strengths typically around 20-30% of their tensile strengths [26, 27]. Considering these constraints, the focus of research has been shifted to interfacial engineering techniques mainly, surface functionalization, CNT coatings, and hierarchical reinforcement frameworks, seeking to improve the overall structural efficiency of aramid-based composites, increasing load transfer capability, and inhibiting crack propagation [12, 24, 28].

1.4. Role of CNTs

CNTs have become the most prominently known nanomaterials since, carbon atoms establish covalent bond formation among them, resulting in the stable configurations in existence [29, 30, 31]. They exhibit remarkable electrical and thermal conductivity, with tensile strengths of approximately 100 GPa, elastic moduli close to 1 TPa, and nanoscale aspect ratios that enable effective stress redistribution [30, 32, 33]. They may function as interfacial engineering tools, strengthening both the constituent and crucial interphase regions in contrast to conventional fillers, and also can be incorporated into aramid nanofiber sheets, integrated as laminate layers, coated onto aramid fibers, or distributed throughout the matrix, depending on the structural arrangement [34, 35, 36].

The mechanism of CNTs displays the enhanced performance of aramid composites in numerous ways, mainly, by improving matrix stiffness, dispersing localized stresses, bridging microcracks, roughening of fiber surfaces, increasing interfacial friction, and forming percolating networks for multifunctionality [30, 34, 36]. These advantages, however, have been influenced by the dispersion quality, functionalization technique, and loading threshold [24, 30, 37]. Depending on the concentration of CNTs, composite properties get affected as the concentration of CNTs exceeds, causing frequent agglomeration and thus resulting in stress concentrators that impair the mechanical performance of composites [30, 38, 39]. CNTs must, therefore, be considered as specific structural design elements rather than any simple modifications [30]. In one such study, the interfacial friction and increased surface roughness showed the CNT-coated aramid fibers significantly improved mechanical performance and tribological properties. Additionally, the CNT-aramid interactions shown by the molecular researchers confirmed the alteration of stress transmitted within the material [24].

1.5. Scope of this Review

This article exploits the structural optimization centered on mechanism-based design to comprehensively evaluate aramid-CNT composites. It solely emphasizes on interphase engineering, architectural selection, and reinforcing mechanism controlling bulk mechanical behaviour instead of presenting a general overview of CNT-enhanced composites. The review also provides optimal design methodologies, resolving conflict findings, and proposes predictive mechanisms for structural engineering of aramid-CNT systems by combining literature from the flexural, tensile, fatigue, and tribological domains.

2. Structural Architecture and Characteristics of Aramid-CNT Composites

2.1. Composite Configurations and Architectures

Unique reinforcement pathways have been offered by aramid-CNT composites which exist across multiple hierarchical configurations [36]. Matrix-dispersed CNT systems have been highly sensitive to dispersion quality, enhance matrix crack resistance and stiffness [30]. CNT-coated aramid fibers primarily strengthen the interphase through roughness, interlocking, and friction enhancement [34, 24]. The interlayers of CNT inserted between laminate plies improve delamination resistance and energy dissipation [40, 41]. These architectures differ fundamentally in reinforcement mechanism. Matrix dispersion primarily improves matrix-dominated properties, coatings optimize interface-dominated behaviour, interlayers target laminate toughness, and ANF-CNT systems provide integrated structural-functional performance [30, 24]. Wang and co-workers demonstrated that the CNT interlayers between hybrid carbon and aramid laminates, through crack deflection and interfacial bridging, significantly improved interlaminar toughness, while ANF-CNT papers offered superior multifunctional structural performance due to continuous conductive reinforcement networks [22]. Consequently, architecture selection must align with target applications rather than assuming universal superiority [42].

By co-processing PA (polyaromatic amide) and CNTs in a LLC wet-spinning dope solution, where spontaneous self-assembly of PA-CNT produced a nematic LLC mesophase that emerged from the spinneret into the coagulant bath, Ryu et. al. fabricated a monofilament PA, aramid-CNT composite fibers with minimal aggregation of CNT and high uniaxial orientation. This resulted in a lightweight but mechanically strong, thermally, physically and chemically resilient conductor. By enhancing load transfer throughout the aligned CNT-aramid framework and generating effective percolated paths for charge transport, this LLC-governed interfacial design improved tensile properties, electrical conductivity, and electrochemical sensitivity of the fibers [43].

2.2. Interphase Engineering

Interphase engineering represents the most critical design variable in aramid–CNT systems because it governs how effectively nanoscale reinforcement translates into macroscale performance [24]. Surface functionalization methods such as acid oxidation, PDA/PEI coatings, hyperbranched polymers, and CVD-grown CNT forests all aim to improve chemical compatibility, mechanical anchoring, and hierarchical structural continuity [36, 24]. It controls how nanoscale reinforcement translates into macro-scale performance [44]. Techniques include silanization [45], polydopamine coatings [46], polyethyleneimine grafting [47], acid oxidation of CNTs [38], hyperbranched epoxy modification [48], CVD-growth [49], in situ polymerization [50], and electrophoretic deposition [51]. The balance among chemical bonding, mechanical interlocking, CNT dispersion, and structural integrity has been altered by each method, whereas stress transfer efficiency, crack propagation resistance, and energy dissipation has been governed by the interphase [21, 36, 48]. CNT incorporation has modified this region by increasing the roughness, creating bridging networks, and establishing both physical and chemical reinforcement pathways [24, 34, 48].

Table 1. Structural Architectures of Aramid–CNT Composite Systems

Types of structural architecture	CNTs location	Primary mechanism	Advantages	Limitations	References
Matrix-dispersed CNTs	Polymer matrix	Matrix stiffening, crack bridging	Improved bulk stiffness	Agglomeration risk	[30]
CNT-coated fibers	Fiber surface	Interlocking friction, adhesion	Strong interphase	Processing compexity	[24]
CNT interlayers	Between plies	Delamination resistance	Improved impact/ flexural performance	Localized reinforcement	[40]

Table 2. Major Fabrication and Interphase Engineering Techniques

Technique	Mechanism	Advantages	Limitations	Reference
Acid Functionalization	Covalent bonding	Strong adhesion	CNT damage	[48]
PDA/PEI Coating	Bio-inspired chemical anchoring	Versatile, scalable	Moisture sensitivity	[51]
Hyperbranched Epoxy Grafting	Dense crosslinking	Toughness enhancement	Complex synthesis	[52]
CVD-CNT Growth	Direct fiber anchoring	Superior load transfer	Thermal constraints	[49]
Interfacial Polymerization	Molecular alignment	Controlled nanostructure	Processing complexity	[43]

3. Mechanical Performance of Aramid-CNT Composites

3.1. Tensile Properties

A crucial aspect in determining the stiffness and strength of the aramid-CNT composites has been governed by the interphase quality [21, 24]. The effectiveness of the stress transfer among the CNTs, aramid reinforcements, and matrix has been crucial in determining the tensile strength of the composites [48]. According to various studies, the inclusion of well-dispersed CNTs enhances fiber-matrix adhesion, bridges microvoids, and avoids the fracture initiation that dramatically improves the tensile characteristics [30]. A recent study on MWCNTs were introduced into heterogenous Kevlar/carbon fiber reinforced composites and epoxy by Sulaiman and coworkers utilizing the vacuum-facilitated assembly and accelerated shear mixing to produce homogenously dispersed CNT within the epoxy matrix. The lower concentrations and consistent distribution of MWCNTs enhanced the bonding between the fibers and the matrix at the interface. The ideal loading of CNTs showed improvements in the tensile strength and modulus with 29.3% and 14.8%, respectively [53].

As demonstrated by the earlier work, CNT dispersion, concentration, and aspect ratio have a significant influence on the tensile properties. Increased resin viscosity, agglomeration, and sites with stress concentration caused by elevated CNT loading frequently counters the benefits of reinforcement, leading to lower tensile performance [48].

3.2. Flexural and Bending Performance

The increase in delamination and interfacial crack propagation caused by the bending stresses leaves flexural properties susceptible to interphase design [21, 24]. For this, the CNT interlayers and coating on the fibers block the propagation of cracks, stresses dispersion, and improvement in the laminate cohesiveness, resulting in the enhanced flexural strength [54, 55]. By integrating CNTs specifically at the xenogeneic (carbon–Kevlar) interfaces instead of distributing them throughout all the interlayers, Jiang et. al. explored a highly effective interlayer stiffening strategy for the polymer composites reinforced by the carbon/Kevlar hybrid fibers. The flexural properties and failure factors were examined by microscopy and three-point bending tests. Furthermore, the optimum CNT-toughened xenogeneic interactions exhibited enhancements in flexural modulus of 26.06%, preliminary and ultimate failure flexural strength of 13.84% and 18.73%, respectively, increased energy absorption and bending stiffness. The reinforcement mechanism was identified as prevention of premature delamination, elevated fracture resistance at xenogeneic layers, and interlayer reinforcement by CNT linkage across carbon-Kevlar interfaces. CNT interleaves contributed to superior flexural performance by efficient stress transfer among various fibers, suppression of Kevlar fiber extension under compression, and facilitation of crack-bridging among subsequent layers [56].

3.3. Impact and Ballistic Performance

Impact and ballistic performance have been considered to be beneficial for incorporating CNTs into aramid composites since, they improve energy dissipation, inter-yarn friction, crack arrest, and delamination resistance under high-strain-rate loading [12, 56]. Surface-grown CNTs improved resistance to yarn slippage and energy absorption under ballistic circumstances by increasing the static friction coefficient by 26.7%, pull-out force by 66.2%, and intra-yarn shear resistance by almost thrice on para-aramid textiles [57, 58]. Liu et. al. developed a multifunctional CNTs/STF/Kevlar composite by incorporating CNTs and mesoporous silica (M-SiO_2) into an ionic-liquid-based STF (shear thickening fluid), followed by a diluting–impregnating–drying process on Kevlar fabrics to obtain conductive, flame-retardant, and impact-resistant wearable composites. SEM, rheological analysis, yarn pull-out tests, ballistic testing, and flammability analysis confirmed the STF-treated Kevlar exhibitingan enhanced dynamic toughness and energy dissipation compared with the neat Kevlar. Unlike conventional bulk, CNT systems that mainly reinforce the matrix through stiffness enhancement, the STF system provided rate-dependent protection by undergoing liquid-to-solid transition under impact, while the hybrid CNTs/STF system combined shear thickening behavior with conductive CNT networks for simultaneous impact sensing and protection. The yarn pull-out force increased by 3–4 times at 55 wt% STF loading, and the composite remained intact under a bullet impact velocity of 110 m/s, whereas neat Kevlar was penetrated. The reinforcement mechanism involved STF-induced frictional locking between Kevlar yarns, CNT-assisted energy dissipation, conductive pathway formation, and particle-cluster formation that improved low-velocity impact resistance, ballistic protection, and dynamic stress distribution while suppressing yarn slippage and localized failure [59].

3.4. Fatigue and Creep Behaviour

The addition of CNTs to the aramid composites has been shown to improve the fatigue resistance and creep stability by enabling interfacial stress transfer, preventing microcrack formation, and distributing the cyclic loads throughout the composite structure. The CNT networks act as nanoscale bridges that interrupt crack nucleation and decrease crack propagation rates under cyclic loading, resulting in higher fatigue life and enhanced damage tolerance [60]. Molecular scale studies have also shown that strong CNT–polymer interactions inhibit polymer chain mobility and enhance load-transfer efficiency, thus decreasing creep deformation under sustained mechanical stress [61]. Handhyal et. al. fabricated Kevlar/hemp/CNT-reinforced epoxy hybrid composites containing 0.5, 1.0, and 1.5 wt% CNTs using the manual lay-out technique to evaluate their fatigue, wear, water absorption, and durability characteristics. Fatigue, wear, density and moisture absorption tests were performed and the results indicated that the use of CNTs significantly improved the long-term durability by improving fiber-matrix bonding and stress distribution in the composite structure. The composite containing 1.5 wt% CNTs showed the maximum fatigue life (12,290 cycles) and the minimum wear rate, with a lower void content (1.20%) and reduced water absorption compared to lower CNT loadings. The reinforcement mechanism involved CNT-mediated crack bridging, restriction of matrix deformation, improved load transfer between Kevlar, hemp fibers and epoxy, with suppression of microcrack growth under cyclic loading. These effects resulted in improved fatigue resistance, creep resistance, structural stability and overall long-term durability, indicating the potential of CNT-reinforced Kevlar-hemp composites for demanding engineering applications.Consequently, CNT reinforcement significantly improved fatigue resistance, creep resistance, thermo-mechanical stability, flame retardancy, and long-term durability of the Kevlar/epoxy composite system [62].

3.5. Tribological Performance

CNT coatings reduce friction coefficients and wear rates by providing self-lubricating graphitic surfaces while simultaneously increasing hardness and contact stability [63]. Studies have demonstrated that CNT-coated aramid fibers exhibit markedly improved tribological behavior due to synergistic hardening and lubricating effects.Wear rates and friction coefficients are usually significantly reduced if the CNTs are well-dispersed or coated onto the fiber surfaces [64].

Table 3. Quantitative Mechanical Performance Trends in Aramid-CNT Composites

Property	Typical Improvement Range	Dominant Mechanism	References
Tensile strength	10–45%	Load transfer, matrix stiffening	[48]
Flexural strength	15–55%	Delamination suppression	[55]
Impact resistance	20–60%	Crack arrest, friction	[58]
Fatigue life	25–200%	Crack suppression	[59]
Wear resistance	20–70%	Lubrication, hardness	[63]

4. Hybrid-Fiber Reinforced Composite Systems

Hybridization with carbon fiber, basalt fiber and thermoplastics extends performance envelopes by integrating complementary reinforcement characteristics [65]. Carbon fiber improves stiffness, basalt improves thermal stability and thermoplastics improve ductility [66, 67, 68]. Meta-aramid systems are often favored for thermal applications, whereas para-aramid systems dominate structural and ballistic sectors [28].

Hu et. al. compared ultra-thin CNTs, aramid pulp (AP), PBO fiber, and graphene interlayers for improving the impact resistance of carbon-fibre-reinforced composites fabricated with low-density interlaminar reinforcements. SEM analyses of the CAI (compression-after-impact), low-velocity impact and damage morphology showed that the CNT interlayers were uniformly distributed in the epoxy-rich areas and provided the greatest residual compressive strength after impact, increasing the CAI strength by 37.8% compared to unreinforced laminates. The reinforcement mechanism between adjacent plies included CNT pull-out,nano-scale crack bridging, suppression of delamination growth and improved interfacial toughness by effective stress transfer. Compared with aramid pulp and PBO interlayers, CNTs provided better damage tolerance due to their ability to penetrate fiber gaps and reinforce multiple crack paths, while graphene interlayers exhibited poor impact performance owing to weak interfacial bonding and graphene delamination. The study showed the effectiveness of ultra-thin interlayers based on CNTs for hybrid laminate systems, resulting in significantly improved impact resistance, residual strength and overall structural synergy without further increase in the laminate thickness[69].

5. Contradictions In Literature And Mechanism-Based Resolutions

Based on the literature works on aramid-CNT composites, contradictory outcomes have been reported due to the differences in CNT loading, dispersion quality, structural architecture, and functionalization strategy [22, 24, 49]. Interpretation governed by the mechanism has resolved these contradictions by recognizing CNTs not being universally beneficial; rather, their reinforcement efficacy depended on architectural optimization [73, 74, 75]. Low CNT additions

Table 4. Comparison of major hybrid Aramid-CNT composite architectures, reinforcements mechanism, and resulting structural performance enhancements.

Sr. No.	Hybrid System	Composite Constituents	Reinforcement Mechanism	Property Improvements	Applications	References
1.	Basalt Fiber–Aramid–CNT Hybrid	Basalt fiber + aramid fiber + CNTs	Multiscale crack deflection and energy dissipation	Enhanced thermal stability and impact performance	Structural and protective applications	[68]
2.	Aramid–CNT–Graphene Hybrid	Aramid fiber + CNTs + graphene derivatives	Percolated reinforcement network	Improved strength, conductivity, and EMI shielding	Multifunctional composites	[70]
3.	Aramid–CNT–MXene Hybrid	Aramid fiber + CNTs + MXenes	Combined load transfer and conductive pathways	Enhanced EMI shielding and thermal management	Aerospace electronics and defense	[71]

Table 5. Mechanistic interpretation of contradictory findings reported in aramid–CNT composite literature and corresponding resolution strategies

Reported Contradictions	Literature Observation	Underlying Cause	Mechanism-Based Resolution	References
CNTs improve tensile strength vs CNTs reduce tensile strength	Some studies report 10–45% improvement while others report deterioration	CNT agglomeration at high loading	Maintain optimum CNT concentration and uniform dispersion	[48]
Covalent functionalization enhances performance vs decreases performance	Improved interface but reduced intrinsic CNT strength	Graphitic defect formation during oxidation	Balance functionalization level to preserve CNT integrity	[78]
Matrix-dispersed CNTs outperform coatings vs coatings outperform matrix dispersion	Conflicting reinforcement efficiencies	Different failure modes and architectures	Select architecture according to target property	[24]
Increased CNT loading improves properties vs excessive CNT loading reduces properties	Nonlinear property trends	Agglomeration and viscosity increase	Operate within optimum loading range (typically 0.3–1.5 wt%)	[39]
CNT-coated fibers show superior IFSS vs minimal improvement	Wide variation among studies	Differences in coating uniformity and surface chemistry	Standardize deposition and functionalization protocols	[64]

generally improved structural performance because dispersed nanotubes acted as effective stress-transfer bridges and crack arrestors [30, 39, 76]. However, beyond critical percolation thresholds, nanotube agglomeration created stress concentration sites, destroying matrix continuity, and weakening bulk performance [38, 39, 72]. Similarly, non-covalent strategies preserved intrinsic CNT properties but provided weaker adhesion whereas, covalent functionalization also improved the bonding while damaging CNT graphitic integrity [39, 77, 78].

6. Mechanism-Based Structural Reinforcement Framework

The mechanical superiority of optimized aramid–CNT systems have been raised by several interactions operating across the scales [24, 61, 76]. CNT bridging directly transfers stress across cracks and weak interfaces [30, 33, 61]. Crack deflection increases fracture path tortuosity, thereby increasing energy dissipation [30]. Mechanical interlocking enhances fiber–matrix friction and pull-out resistance [21, 24]. Percolation networks redistribute loads across multiple pathways, reducing localized failure [76, 79]. Chen et. al. fabricated continuous aramid fiber/unsaturated polyester composites by constructing a PEI–PDA multifunctional interlayer on aramid fibers followed by co-grafting of NH_2-CNTs and COOH-CNTs, creating a robust nano-hierarchical reinforcement interface. The synergistic CNT modification significantly enhanced aramid fiber interfacial compatibility and load transfer, increasing interfacial strength to 39.60 MPa (with 81.15% improvement) and tensile strength to 1404.25 MPa (with 89.45% improvement) compared with untreated AF/UP composites. Dense CNT grafting, improved surface roughness, strong chemical bonding, and formation of conductive pathways were all revealed by SEM, TFBT (Transverse bundle testing), FTIR, tensile test, and electrical resistance. The reinforcement mechanism involved PEI–PDA-mediated covalent anchoring of NH_2/COOH-CNTs, enhanced mechanical interlocking, hydrogen bonding, crack-bridging by CNT networks, and efficient stress transfer across the aramid fiber–polyester interface. The dual-functional CNT network also imparted semiconductive behavior (51.57–84.20 MΩ), enabling potential structural health monitoring while maintaining excellent mechanical performance and multifunctionality [80].

Table 6. Reinforcement Mechanisms Across Scales

Scale	Mechanism	Structural Effect	References
Molecular	Chemical bonding	Improved adhesion	[21]
Nanoscale	CNT bridging	Stress transfer	[61]
Microscale	Crack deflection	Toughness enhancement	[79]
Macroscale	Hierarchical architecture	Bulk structural optimization	[76]

7. Critical Gaps and Future Directions

On contrary to enormous advancements, due to certain unresolved challenges as scalable CNT dispersion, cost-effective manufacturing, standardized optimization protocols, and limited durability studies, aramid-CNT composite systems remain constrained under realistic conditions. Many studies remain highly system-specific, making cross-study comparisons difficult. Furthermore, the absence of unified structural design principles has limited industrial translation. Future research must prioritise predictive model optimization, scalable hybrid architectures, environmentally sustainable processing routes, and multifunctional systems that integrate sensing, thermal regulation, and structural health monitoring. The next frontier lies in treating aramid–CNT systems not merely as reinforced materials, but as architectured structural platforms where interphase engineering drives holistic performance.

8. Conclusion

Structural optimization governed by a mechanistic approach essentially modifies the design philosophy of aramid–CNT composites. Rather than focusing solely on constituent enhancement, modern composite performance is governed by the strategic engineering of interphases, hierarchical architectures, and multiscale reinforcement mechanisms. CNTs provide transformative opportunities to overcome longstanding limitations of aramid systems, but their true potential is only realised when loading, dispersion, functionalization, and architecture are co-optimised. Thus, integrating the reinforcing strategies within a structural framework design along with addressing contradictions in the existing investigations, this review proposes a new paradigm for aramid-CNT composite engineering. This approach has been vital for developing advance composites that are lightweight, high-strength, multifunctional composites capable of meeting the increasingly demanding requirements of aerospace, defence, wearable systems, and next-generation structural technologies.

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