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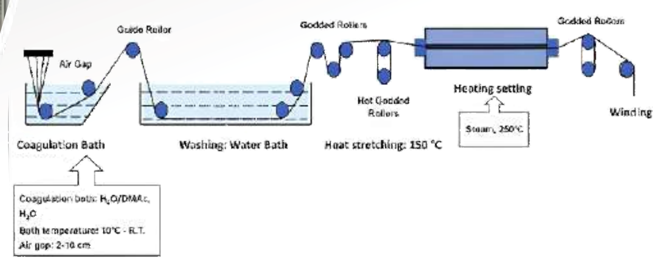

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EDITOR'S DESK

Dear Readers,

Greetings!!

Research with persistent and focused efforts lead to a positive result. Fostering research and providing a platform to publish quality research papers and related articles has been a continuous effort of BTRA Scan. We are working hard to help the journal in climbing up the ranking ladder. In continuation to this effort, I am delighted to present to our readers the 3rd issue of 55th Edition of BTRA SCAN.

This issue has 3 papers from the different domains such as Impact of the Global Energy Crisis on Textile Manufacturing: A Strategic Roadmap, Manpower Planning and Assessment in a Textile Mill - Part I and Mechanistic Approach Towards Structural Design of Aramid-CNT Composites: Bulk Performance Optimization, Multiscale Reinforcement, and Interphase Engineering. Now we are open for authors from outside so researchers can send their original articles, case studies, research reviews or empirical contributions for publication in our journal.

I thank my entire publishing team for all their support. Together we would work towards making the journal a truly influential publication. Comments and suggestions are always welcome.

Our sincere thanks to all the reader and contributors for their support and interest.

T V Sreekumar, PhD
Director, BTRA

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Impact of the Global Energy Crisis on Textile Manufacturing: A Strategic Roadmap

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Abstract

The textile manufacturing sector has experienced unprecedented energy-related challenges in recent years due to volatile fuel markets, geopolitical instability, and increasing electricity prices. These developments have significantly influenced production costs and operational efficiency, particularly in developing economies. This paper analyses these impacts on India's textile industry and proposes practical engineering strategies for improving energy resilience through renewable energy integration, process optimisation, digital energy management, and waste heat recovery.
India's textile industry, one of the world's largest employers, depends heavily on thermal and electrical energy for spinning, weaving, wet processing, garmenting, and finishing. Escalating energy costs have driven up production expenses, reduced global competitiveness, and affected export performance.

This paper examines the technical and economic impacts of the energy crisis on textile manufacturing in developing countries, with a special focus on India. It also presents a practical strategic roadmap centred on renewable energy adoption, open-access power procurement, energy-efficient technologies, digitalisation, waste heat recovery, and policy support. The study concludes that long-term resilience can only be built through integrated energy planning, technological modernisation, and sustainable manufacturing practices.

Keywords

Global energy crisis, textile industry, India, energy management, renewable energy, sustainability, strategic planning, industrial resilience

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1.0 Introduction:

The global energy crisis gained momentum after the COVID-19 pandemic, driven by geopolitical tensions, fuel supply disruptions, inflation, and surging energy demand. Conflicts such as the Russia-Ukraine war and instability in the Middle East caused sharp volatility in crude oil and natural gas prices, severely affecting manufacturing worldwide. Developing countries suffered even more due to heavy reliance on imported fossil fuels and weak energy infrastructure.

Textile manufacturing requires substantial quantities of both electrical and thermal energy because every stage of production, from fibre preparation to finishing, depends on energy-intensive equipment. Wet processing operations account for the highest thermal demand owing to repeated heating, washing, drying, and curing processes.In India, energy costs typically account for 15–20% of total textile production costs, making energy a critical factor for profitability.

India's textile sector plays a vital role in the economy, contributing significantly to GDP, exports, and employment. It directly employs over 45 million people and is concentrated in major clusters such as Bhiwandi, Malegaon, Ichalkaranji, Surat, Ahmedabad, Tirupur, and Ludhiana. However, rising electricity tariffs, fuel shortages, and price volatility are threatening the industry's sustainability and competitiveness.

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2. Global Energy Crisis: Background and Causes

2.1 Major Causes and Their Impact

Factor	Impact on Textile Industry
Geopolitical disturbances	Sharp rise in natural gas and crude oil prices
Supply chain disruptions	Delays in coal and fuel procurement
Inflation & currency issues	Higher cost of imported fuels
Power shortages	Frequent production interruptions
Rising industrial demand	Increased electricity tariffs
Climate regulations	Higher compliance costs

Global crude oil prices surged between 2022 and 2025, directly affecting transportation, synthetic fibre production, chemicals, and thermal energy generation. Textile units relying on diesel generators, furnace oil, coal, and natural gas faced severe cost increases. Many processing units in western India reported significant financial stress due to rising diesel and fuel prices.

3. Energy Consumption Pattern in Textile Manufacturing

Textile production is highly energy-intensive, with different stages requiring different forms of energy.

3.1 Energy Consumption by Process

Textile Process	Major Energy Source	Approximate Share
Spinning	Electricity	35–40%
Weaving / Knitting	Electricity	15–20%
Wet Processing	Steam + Electricity	30–35%
Garmenting	Electricity	5–8%
Utilities	Thermal + Electrical	10–15%

Source: https://www.mdpi.com/, https://textilelearner.net/, https://www.sciencedirect.com/,https://www.fibre2fashion.com/

Wet processing generally accounts for the highest thermal energy demand in textile manufacturing due to extensive heating and drying operations (Hasanbeigi et al., 2022).

"The textile industry is among India's major industrial consumers of coal, natural gas, biomass, furnace oil and electricity."

4. Impact of the Global Energy Crisis

4.1 Rising Production Costs

Escalating fuel and electricity prices have increased the operating cost of boilers, thermic fluid heaters, compressed-air systems, and process heating equipment. Consequently, manufacturers have experienced reduced operating margins, particularly in export-oriented textile clusters where energy constitutes a significant share of production costs.In many clusters, electricity tariff hikes have squeezed profit margins and weakened export competitiveness.

4.2 Production Disruptions

Power shortages and unstable fuel supply have led to machine downtime, reduced capacity utilisation, delayed shipments, and longer lead times. Several units in Gujarat and Maharashtra were forced to cut production during the peak crisis periods.

4.3 Decline in Export Competitiveness

Elevated energy costs have raised the prices of fabrics and garments, making Indian products less competitive compared to countries with subsidised power or lower energy costs.

4.4 Disproportionate Impact on MSMEs

Small and medium enterprises have suffered the most. Limited capital, outdated machinery, dependence on conventional energy, and poor energy efficiency have left them highly vulnerable.

5. Technical Analysis of Energy Consumption

Equipment	Energy Type	Key Efficiency Concern
Boiler	Thermal	Heat loss
Thermo-pack	Thermal	Combustion inefficiency
Stenter	Thermal + Electrical	Exhaust heat loss
Air Compressor	Electrical	Leakage losses
Dyeing Machine	Thermal	Steam wastage
Chiller	Electrical	High peak demand
Motors & Pumps	Electrical	Overloading

5.1 Major Energy-Consuming Equipment

5.2 Typical Energy Losses

- Steam leakage: 5–10%
- Condensate loss: 10–15%
- Improper insulation: 5–8%
- Compressed air leakage: 20–30%
- Inefficient motors: 8–12%

Well-planned energy audits and process optimisation can deliver substantial savings.

6. Strategic Roadmap for India

6.1 Renewable Energy Integration

Indian textile companies are gradually shifting towards solar power, biomass boilers, wind energy, group captive projects, and open-access renewable procurement. The share of renewables in the sector's power consumption rose from around 14% in FY2023 to nearly 18% in FY2025.

Recommended Renewable Strategy

- Rooftop Solar → Best suited for garmenting and spinning units
- Biomass Boilers → Ideal for wet processing
- Group Captive Solar → Suitable for integrated mills
- Wind Power → Large industrial clusters

6.2 Open Access Power Procurement

Open-access buying can cut power costs by 15–30%, reduce dependence on state utilities, and improve reliability. Clusters in Maharashtra and Gujarat are increasingly adopting captive and group-captive renewable models.

6.3 Energy Efficiency and Conservation

Measure	Potential Savings
VFD installation	10–20%
Waste heat recovery	15–25%
Condensate recovery	10–15%
LED lighting	5–8%
High-efficiency motors	5–12%
Heat pump technology	20–40%

Source: https://ingener.by/, https://www.sciencedirect.com/, https://www.researchgate.net/

6.4 Digital Energy Management

IoT-based monitoring, AI-driven predictive analytics, real-time dashboards, and smart load management can significantly improve efficiency.

6.5 Sustainable Wet Processing

Adopting low liquor ratio dyeing, cold pad batch processing, enzyme-based methods, heat recovery systems, and water recycling can reduce both energy use and environmental impact.

7. Policy Recommendations

The government should focus on:

- Higher subsidies for renewable energy adoption by MSMEs
- Simplified open-access regulations
- Mandatory periodic energy audits
- Low-interest green financing
- Incentives for carbon reduction and cleaner production

8. Proposed Strategic FrameworkIntegrated Energy Resilience Framework

Phase 1: **Assessment –** Energy audits, baseline mapping, and benchmarking

Phase 2: **Optimisation –** Utility modernisation and efficiency improvements

Phase3: **Renewable Integration –** Solar, biomass, and captive power projects

Phase 4:**Digital Transformation –** Smart monitoring and predictive maintenance

Phase 5: **Sustainability Compliance –** Carbon tracking, ESG reporting, and circular practices

9. Future Outlook

The textile industry of the future will rely on renewable energy, smart manufacturing, sustainable processing, energy-efficient machinery, and circular economy principles. Companies that act early will enjoy lower costs, stronger export competitiveness, better ESG performance, and long-term sustainability. Developing economies must move from reactive crisis management to proactive energy resilience planning.

10. Conclusion

The global energy crisis has clearly exposed the vulnerabilities of textile manufacturing in developing countries. In India, rising energy costs, operational instability, and growing sustainability demands present serious challenges. Yet, this crisis also offers a valuable opportunity to modernise the industry.

By adopting renewable energy, improving efficiency, embracing digital tools, and implementing supportive policies, India can build a more resilient and competitive textile sector. Sustainable energy planning is no longer optional — it has become essential for survival and future growth.

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Manpower Planning and Assessment in a Textile Mill - Part I

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Abstract
Textile industry being a major employment consuming industry in the country and also it has different activities across the value chain of fibre to fashion and their interlinking also is complex depending upon the business model used by various entrepreneurs.The manpower availability with right skills and its planning becomes critical and important forthe human resource department in a textile mill.The objectives, key steps, tools and techniques used in the process of manpower planning and assessment are explained in this paper. Also, this paper throws the light on work force behavioral aspects impacts on it and the challenges faced by the HR department in this process are discussed in this paper series part 1.

Key words:
HR department, manpower planning, skills, productivity, efficiency, machine utilization, operational goal, behavior, tools and techniques, assessment, time motion study,

Citation
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1. Introduction:

As all of us are well aware that the textile industry is one of the large scale industry in our country and majorly provide the employment in the large extent. The both types of workforce i.e. skilled and unskilled are required throughout the various stages of textile production. The employment is depending on various factors like mill size, product type being manufactured, type and technology in machines, technology upgradation, automation on the machine and production rate etc. Manpower planning is essential in a textile mill to ensure that the right quantity of manpower with right skill set is available as and when needed. For the cost optimization or control, along with machine utilization optimization, productivity improvement the man power optimization is also an important factor. Particularly, large scale factories need to understand the manpower requirement with proper Skill availability to sustain the business in this competitive market. The industry also faces challenges related to skilled manpower shortages and the impact of technological advancements on employment in industry 4.0.The industry 4.0 is the continuous computerization of conventional assembling and modern works utilizing presently available brilliant innovations[1] The present paper series , particularly this part 1 focuses on the aspects like the purpose of manpower planning in a textile mill, main steps in manpower planning, the sections or departments typically covered in a textile mill, different tools and technique used for monitoring and assessment and the challenges faced by textile sector for manpower availability and planning. In the upcoming next part , the existing manpower assessment methodology will be addressed.

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2. Manpower planning purpose in a textile mill

The purpose or objective of the manpower planning in typical textile mill can be listed as below;

a) To ensure sufficient or optimum manpower across all departments like warehouse, production, engineering, quality assurance ,inspection and packing etc so that the activities in this departments runs smoothly.

b) To match workers and staff skills with operational requirements. For example, ring frame spinning , warping and sizing, loomshed, dyeing ,printing, maintenance and ETP operations requires a particular and typical set of skills.

c) To anticipate future demand and hence expansion and automation possibilities and accordingly to have approximate manpower anticipated estimation.

d) To minimize the labour cost by proper allocation defining combination of skill sets and workforce optimization

e) To ensure and improve target productivity, efficiency and utilization of machines and other related resources are achieved.

f) To identify the skill gaps and training needs. This will create a skilled and motivated workforce pool available in the mill.

g) To develop the second and third line workforce in the case of retirement and resignations.

h) To ensure adherence to safety, compliance and regulatory requirements.

i) To evaluate and plan for manpower requirements for futuristic automation and newer and advanced technology adoption through the technology driven training modules.

j) To minimize turnover and absenteeism

3. The various departments to be covered:-

The following table no.1 shows the various departments or functions in a typical textile mill.

Table 1 - Major categories in the various departments in a typical textile mill

Sr. No.	Department name	Type of workforce involved
1	Spinning	Supervisors, quality checkers
1.1	Fibre warehouse	Sorters, loaders , store keeper
1.2	Blow room	Blow room operators and helpers
1.3	Carding	Carding operators and helpers
1.4	Drawing	Draw frame operator and helpers
1.5	Combing	Comber and helpers
1.6	Speed frame department	Speed frame operator, helper and doffer
1.7	Ring frame department	Ring frame operator, helper and doffer
1.8	Winding	Winding operator, helper and doffer /package carriers
1.9	Packing and bale pressing	Packing operator helpers and loading / unloading persons
2	Weaving	Supervisor, quality checkers
2.1	Yarn godown	Loading / unloading persons, store keeper
2.2	Weaving preparatory	Warper, winder, sizer, size cooker, beam loader,
2.3	Weaving	Weaver, checker, designer, weft boy, Cloth doffer, Beam gaiter, knotting persons, jobber, bobbin/reel maker
2.4	Grey inspection	Mending person, fabric inspector, quality checker, roll organiser
2.5	Packing and dispatch	Roller/folder, packer, forklift operator.
3	PPC department	Planner, PPC executive, data entry operators
4	Wet processing	Supervisors, dyeing master, printing master
4.1	Bleaching	Machine operators, helpers, material handlers
4.2	Dyeing	Machine operators, helpers, shade matchers, material handlers, colourman, colourist, chemical store keeper
4.3	Printing	Designer, screen maker, screen expos ure printers, helpers, shade matchers or colour makers or mixers, chemical store keeper
4.5	Finishing	Machine operators, helpers, Kanji man
4.6	Folding/inspection department	Fabric inspectors, packers, rollers, folding machine operators , helpers, chindi sorters, labeler, data entry operator, forklift operators
5	Quality assurance	QC inspectors, lab technician, Testers, process control monitors, colorist, data entry operator,
6	ETP	ETP operator, sampler, water analyst, data entry operator
7	Utility and maintenance	Engineers, fitters, oilers, electricians, compressor operators, boiler operators, mechatronics
8		Data Entry Operator,

4. Main steps of the manpower planning

There are certain sequential main steps in the process of manpower planning in a textile mill those the HR (Human Resource) department should follow for successful and effective planning.

⬇

Evaluating the organization objective i.e. understanding the production and or operational goal and future expansion plans and accordingly to align the manpower requirement against short term and long term business goals.

⬇

Anticipating and estimating the manpower demand for future considering production schedules, new machinery additions or expansions in product line and automation etc.

⬇

Analyse the existing available man power with respect to rolewise/ category wise number, skill set, age , retirement projections, existing production levels and absenteeism. Thus shortages or surplus manpower along with skill mismatches can be evaluated. This may be done by a third party audit called Time motion study which will be discussed majorly in part II of this paper series.

⬇

After this gap analysis, the HR can plan for action to fulfill the same through the recruitment, training and skill development and re-deployment and or readjustment for departmental requirement and skill set matrix.

The above action plan before implementing should be discussed by HR with various department heads, production managers to roll out recruitment and training

⬇

The planned and implemented manpower matrix should be periodically monitored for its effectiveness. During the evaluation again consider production changes as per current demand, labour turnover and new technology available at that time and process change required as per quality and customer demand.

5. Manpower behavioral aspects and Skill

In a textile mill, not only machines and raw material influences the productivity and quality, but also, operator behavior, skill and motivation makes an impact on them. This section explains the various aspects of operator behavior and skills. These aspects are as below mentioned

i. Work discipline, timely joining the duties and attendance of the work force becomes important as the production and shift schedule is tight in a textile production mill. However, certain organizations like educational institutes, research institutes and government related institutes such at ype of flexibility in behavior may be observed.

ii. The team work in certain departments like folding and packing, dyeing and printing, finishing , laboratory, weaving becomes important as the activities are interdependent and hence the communication, collaboration and team-work among these workforce is a must.

iii. Workforce must adopt the automation, new machine addition in the plant, as the resistance to these things may delay the implementation and reduce the efficiency

iv. Motivation has an impact on productivity and quality. However, some higher motivation may cause a burn out effect due to higher and restless workload. The motivation can be achieved by job recognition, incentive schemes and good supervisory skill. Here good supervisory skill need not means less discipline and control over the workforce.

v. Safety , good work environment (means work environment without politics and favoritism among the subordinates) , cultural and social sensitivity impacts the workforce significantly.

vi. By considering the above mentioned aspects of the manpower behavior in a textile mill, the HR department can plan the skill or skill set upgradation programs for the workforce to maintain the competitiveness and to meet the quality standards.

vii. Skill can be technical skills, soft skill/personality development, safety and compliance skills etc.

viii. There are various methods/options of skill available like; on job training, inhouse class room training, training by outside expert, apprenticeship, certification courses by outside agencies, and to create the flexible work force the multi-tasking skill etc.

ix. All these skill programs should be aligned with organization and production goals. The HR department may use behavioural data to improve training and HR interventions.

x. All the skill programs should be finally evaluated and certified regularly.

6. Different tools and techniques used for manpower planning and assessment.

6.1 Tools and techniques used for manpower power planning

The HR department generally uses the tools to forecast the manpower planning depending upon the organization work culture and MIS capability. The various tools and techniques used for workforce planning and assessment are mentioned below;

a) Quantitative Manpower Planning and Forecasting Tools :-Based on the available data from MIS and statistical models, the manpower planning can be done. These are trend analysis or ratio analysis to understand historical production against no. of workers and staff, seasonal or cyclic demand trend of workforce, In the ratio analysis you can consider for example no. of loom per worker, no.

of spindles per worker , staff to worker ratio etc. Furthermore, quantitatively activity mapping may be done and based on these standards the total labour hours and or machine shifts can be estimated for certain production. This can be extended further productivity per worker per shift, machine utilization etc.

b) Qualitative Manpower Forecasting Tools :- The qualitative tools used for manpower forecasting are judgement, analysis of qualitative information like skill inventory, job analysis, opinion of a group of experts and past experience of department heads etc.

c) Strategic Workforce Assessment Tools (SWOT Analysis):- The qualitative analysis may also include SWOT analysis i.e. strength (skill and technology, low absenteeism), weakness (high turnover in the difficult and hazardous task like spinning , chemical storage area), Opportunities (Govt training schemes) and Threat (automation and labour unrest, competitor may use your ready made trained manpower by tempting them for higher salary)

6.2 Tools and techniques used for manpower power assessment

To monitor the performance of the workforce via qualitatively and quantitatively the different tools and techniques are used by an experts and the HR department, which are listed below;

i. Performance appraisal system to identify and reward the high performer. This is generally yearly done activity.

ii. Training needs evaluation is done as and when required based on a daily feedback system.

iii. Employee survey and feedback is taken to understand the work culture, management behavior, level of motivation, job satisfaction and understanding training needs.

iv. Gap analysis for all the above aspects discussed so that corrective measures are taken timely.

v. Work load analysis or time motion studies by third party. This we will discuss in part -II in a more detailed manner.

HR needs to be more digitally focused. HR specialists need to keep up with technology trends to stay ahead of the competition [2]To do quantitative data analysis for both manpower planning and evaluation, the mill can use advanced software tools and digital platforms , applications, like ERP software, Time attendance system, skill mapping matrix software or application , workforce scheduling software etc.

HR needs to be more digitally focused. HR specialists need to keep up with technology trends to stay ahead of the competition.

7. Challenges faced by Textile sector for manpower availability and planning

Textile industry is facing the issue of manpower availability and hence the planning is becoming quite a difficult and uncertain task for HR on a day to day basis. The various reasons can be listed as below;

a) The industry many times struggles for availability of workers or technicians for the specific tasks in the modern textile mills. where advancement, work accuracy and customer demand is high. For example; shade matching expert in dyeing and printing process, warper and sizer, peaching machine operator etc

b) It is also observed that many textile mill operators are near retirement and there's a lack of younger workers interested in the textile field. This may be due to availability of opportunities in other fields like computers/IT, Mall culture and online application based platform services. Also consistency, integrity, reliability and loyalty seems to be inadequate.

c) The emerging "fast fashion, sustainability and eco-friendly products require a specialized knowledge and skilled workforce.

d) Other countries with cheaper labour availability and favorable trade agreement are creating global competition for business and hence pressure on Indian textile manufacturers for innovation and efficiency improvement.

e) During our various studies and visits to textile companies, it was noticed that at many places textile workforce lacks formal training making it challenging to implement new technologies and improve overall productivity. Many time existing manpower tries to resist the new technology implantation and automation due to fear of job displacement or losses and lack of awareness and training for the subject.

f) Promoting and complying with gender equality some time becomes critical in the case of heavy work load, night shift working restrictions, safety concerns, provision of maternity leaves etc. Also, stricter work environment complaisance by legal authorities, safety related aspects, waste and sustainability management needs additional work force and specialized training to them periodically to achieve compliance level.

g) To attract and retain talent is quite challenging for the textile industry due to factors like lower wages compared to competitors and working environment comparison.

h) Among the unskilled and contract basis workers, there is chance of high attrition, and labour turnover problem, uncertain social, economic, environmental and technological developments, Unavailability of funds to meet desired recruitment and training programmes[3] and also everyday workforce changes so production disturbance occurs and also increases short term training cost.

8. Conclusion and way forward

Man power planning is critical and major role of HR in the textile mill. Depending on production trend, technology updatation, automation, seasonal changing demand from market, the behavioral aspect of existing manpower and skill gap analysis and training needs, the HR department plans for manpower deployment. The HR department should review the manpower deployed in the mill against the defined set of production on a monthly basis. There are certain tools used by the HR department to implement and review the planned manpower. Also, atleast at every five years this should be verified with third party by conducting time motion study audits of the workforce and the work being carried out. The same will be discussed in this paper coming part II,

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

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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

Citation

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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].

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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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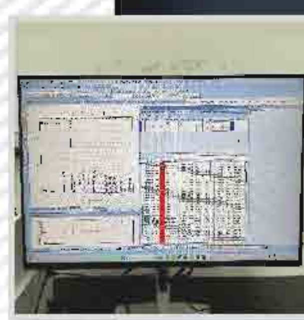

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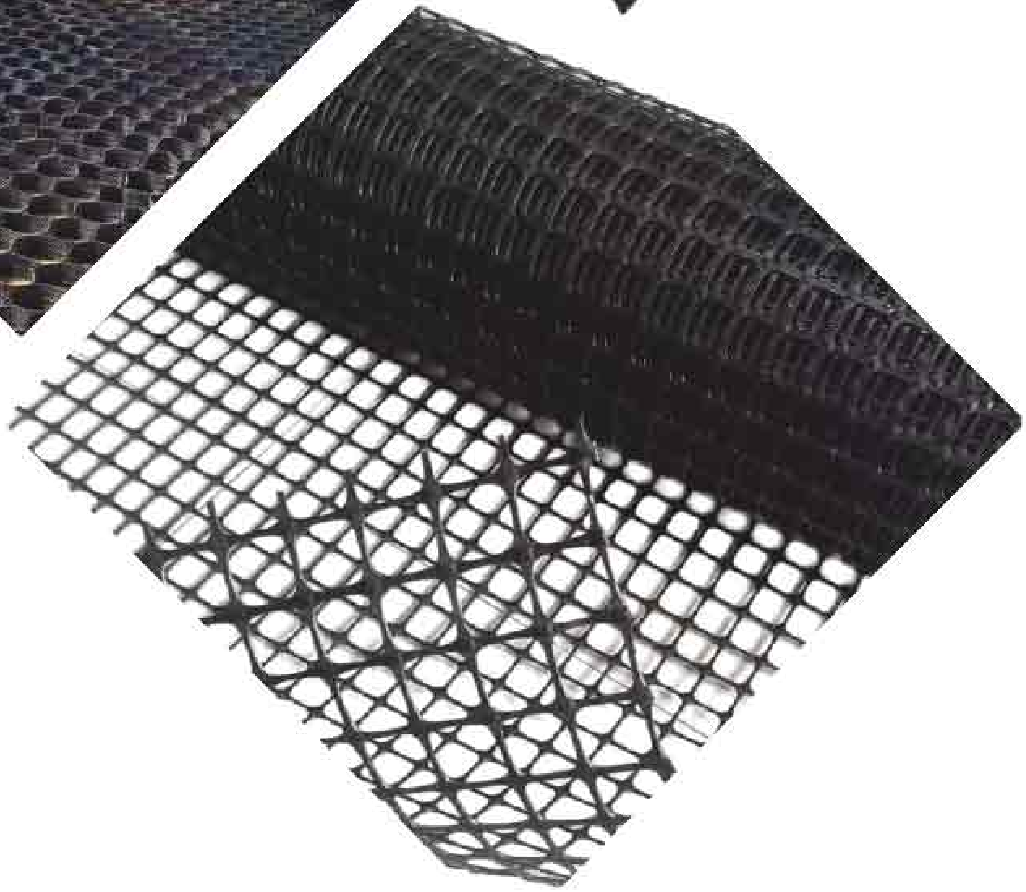

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