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Kevlar K29/PAN-Based Carbon Fibre Hybrid Composites for Aerospace Structures: A Critical Review of Architecture, Processing, Damage and Design

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Abstract: Hybridisation of high-modulus carbon fibres with impact-tolerant aramid fibres is an established strategy for mitigating the brittle damage response of carbon-fibre-reinforced polymers while retaining structural efficiency. This review critically evaluates Kevlar K29/polyacrylonitrile (PAN)-based carbon-fibre hybrid composites for aerospace structures, with emphasis on constituent behaviour, hybrid architecture, manufacturing routes, mechanical performance, damage mechanisms, environmental durability, modelling, inspection and certification. The literature shows that the hybrid effect is not an intrinsic material constant; it emerges from interactions among fibre modulus mismatch, strain-to-failure mismatch, ply location, areal density, matrix toughness, interface chemistry, impact energy and test geometry. Carbon-face/Kevlar-core laminates generally preserve flexural rigidity and compression-after-impact strength, whereas Kevlar-rich outer layers improve penetration resistance and visible damage tolerance at the cost of surface stiffness and compressive stability. Interply hybrids are easier to manufacture and certify, while intraply woven, braided and three-dimensional architectures provide more distributed energy absorption but introduce complex mesoscale stress transfer and modelling requirements. Vacuum infusion, resin-transfer moulding, prepreg-autoclave processing and emerging out-of-autoclave routes are compared in terms of void control, fibre wet-out, thickness uniformity and scalability. Persistent limitations include delamination, moisture-sensitive aramid interfaces, difficult machining, poor through-thickness conductivity, property scatter and a shortage of standardised long-duration fatigue and environmental datasets. A design framework is proposed that links mission loading to laminate architecture, processing quality, damage-tolerance metrics and non-destructive inspection. Future progress requires multi-objective optimisation, physics-informed damage models, in-situ sensing, recyclable matrices and full-scale validation under combined impact, fatigue, temperature and moisture exposure.

Keywords: Aerospace Composites, Aramid Fibre, Carbon Fibre, Damage Tolerance, Hybrid Laminate, Impact, Kevlar K29, PAN-Based Carbon Fibre.

1. Introduction

The aerospace sector has adopted fibre-reinforced polymer composites because structural mass reduction can translate directly into lower fuel consumption, greater payload, increased range and improved manoeuvrability. Carbon-fibre-reinforced polymer (CFRP) is particularly attractive because PAN-derived carbon fibres combine low density with high tensile modulus, high specific strength, fatigue resistance and dimensional stability. These advantages have enabled extensive use in wing skins, spars, fuselage barrels, control surfaces, satellite panels and unmanned aerial vehicles. Nevertheless, laminated CFRP remains vulnerable to low-velocity impact, barely visible impact damage, interlaminar delamination and abrupt fibre-dominated failure [1-4].

Aramid fibres offer a complementary mechanical profile. Kevlar K29 has a density near 1.44 g cm-3, high tensile strength, high strain-to-failure and exceptional capacity to absorb energy through fibrillation, yarn stretching, pull-out and frictional sliding. These attributes are valuable under foreign-object impact, bird strike, tool drop, runway debris and ballistic loading. Its limitations are equally important: comparatively low compressive strength, low transverse stiffness, moisture sensitivity, difficult cutting and machining, and weaker adhesion to common thermoset matrices [5-7].

Hybridising carbon and aramid fibres is therefore appealing because the two reinforcements can be arranged to distribute distinct structural functions. Carbon-rich regions can carry axial and bending loads, while aramid-rich regions can arrest cracks and dissipate impact energy. However, positive hybridisation is not guaranteed. Modulus and failure-strain mismatch can generate interlaminar shear concentrations, premature splitting or localised damage at dissimilar-ply interfaces. The outcome depends on fibre ratio, stacking sequence, orientation, weave, matrix toughness, processing quality and loading mode [8-11].

Recent research has moved beyond simple tensile-property comparison toward low-velocity impact, compression after impact, bending after impact, mixed-mode fracture, fatigue and multi-scale modelling. Studies increasingly examine intraply carbon/Kevlar fabrics, sandwich arrangements, nano-modified interfaces and three-dimensional braids [12-17]. Yet the evidence remains fragmented: test methods differ, many studies use small coupons, and direct comparisons are complicated by differences in areal density, resin content and laminate thickness.

The present review provides a mechanistically organised assessment rather than a descriptive catalogue. It addresses five questions: (i) how do the intrinsic properties of Kevlar

K29 and PAN-based carbon fibre control hybrid response; (ii) which architectures are most appropriate for stiffness-, impact- and fatigue-critical functions; (iii) how do manufacturing defects and interfaces alter the expected hybrid effect; (iv) which experimental and numerical metrics are most meaningful for aerospace qualification; and (v) what research is required to progress from coupon-scale demonstrations to certifiable structures.

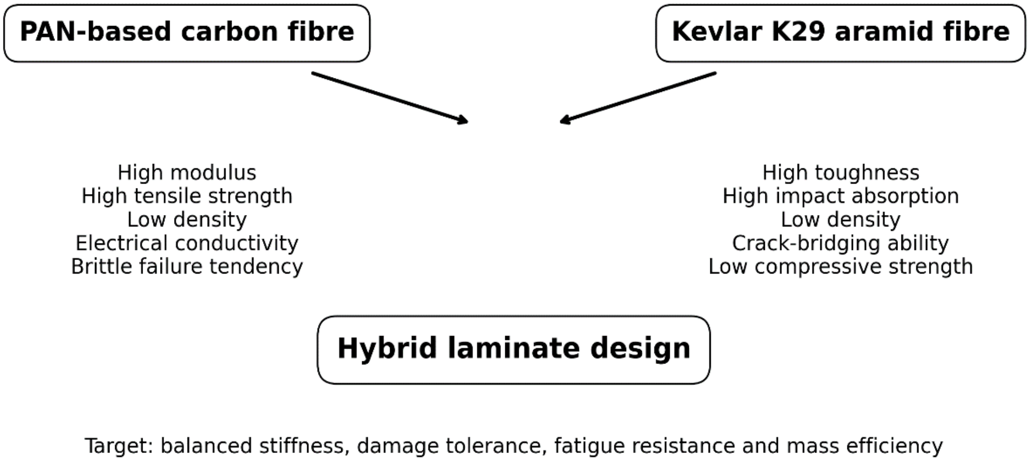

Figure 1. Complementary functions of PAN-based carbon fibre and Kevlar K29 in a structural hybrid laminate.

2. Review Methodology and Scope

The review was structured around peer-reviewed journal articles, authoritative books, technical guides and standards relevant to carbon/aramid hybrid laminates. Priority was given to work published from 2020 onward, while foundational studies were retained where they established hybrid-effect concepts, impact mechanics or laminate design principles. Search themes included carbon-Kevlar hybrid composites, carbon-aramid laminates, low-velocity impact, compression after impact, fatigue, stacking sequence, interply and intraply hybridisation, fracture toughness, non-destructive evaluation and aerospace manufacturing.

Studies were screened for relevance to continuous-fibre polymer composites and for reporting at least one of the following: constituent properties, laminate configuration, manufacturing parameters, mechanical response, damage morphology, numerical validation or aerospace design implications. Papers dealing exclusively with short-fibre concrete, unrelated natural-fibre systems or armour without transferable structural evidence were not used as primary evidence. Because experimental protocols are heterogeneous, the review avoids pooling incompatible strength values into a single meta-analysis. Instead, it compares trends, mechanisms and design consequences.

The evidence was grouped into seven analytical domains: constituent behaviour; laminate architecture; manufacturing and quality; static response; impact and residual strength; fatigue and environmental durability; and modelling, monitoring and certification. This organisation supports a structure-property-processing-damage framework suitable for Q2-level review standards.

3. Constituent Materials and Micromechanical Basis

3.1 PAN-based Carbon Fibre

Most aerospace carbon fibres are produced from PAN precursor by oxidative stabilisation, carbonisation and, for higher modulus grades, graphitisation. Increasing thermal treatment raises carbon ordering and axial modulus but can reduce strain-to-failure. The resulting fibres are strongly anisotropic: axial stiffness and strength are high, whereas transverse and shear properties depend heavily on the matrix and interface. Carbon fibres also provide electrical and thermal conduction paths, which can aid lightning-strike protection and structural-health-monitoring concepts, although a conventional laminate remains insufficiently conductive through the thickness. For hybrid design, the key carbon-fibre attributes are high modulus and relatively low failure strain. Carbon plies placed far from the neutral axis dominate bending stiffness, but they are also susceptible to compressive microbuckling, kink-band formation and brittle fracture after impact. Thus, carbon placement should be treated as a structural variable rather than simply a constituent percentage.

3.2 Kevlar K29 Aramid Fibre

Kevlar K29 is a para-aramid fibre based on highly oriented aromatic polyamide chains. Strong intermolecular hydrogen bonding and chain alignment produce high axial tensile strength and low density. Unlike carbon fibre, aramid develops extensive fibrillation and progressive tensile damage, enabling substantial energy absorption. The same molecular morphology contributes to poor transverse and compressive response because chains are weakly constrained against shear instability and microbuckling. Aramid surfaces are chemically less reactive than many oxidised carbon-fibre surfaces. Moisture uptake and limited wettability can reduce the stability of the fibre-matrix interface, especially after hygrothermal ageing. Plasma treatment, oxidative treatment, silane coupling, nano-coatings and matrix toughening have therefore been explored to improve adhesion, but aggressive treatment can damage fibrils and reduce intrinsic fibre strength.

3.3 Property Complementarity and Hybrid-Effect Definitions

A hybrid effect exists when the measured property of a hybrid differs from the value predicted by a linear rule of mixtures between the corresponding single-fibre composites. A positive hybrid effect may arise from delayed carbon-fibre failure, stress redistribution by aramid plies, crack bridging, enhanced frictional dissipation or confinement of local damage. A negative effect may occur when stiffness mismatch elevates interfacial stress, when resin-rich zones form between dissimilar fabrics, or when low-stiffness aramid layers reduce compressive stability.

The definition must specify the normalisation basis. Comparisons by fibre volume, laminate mass, thickness or cost can produce different conclusions. For aerospace design, specific stiffness, specific residual strength, absorbed energy per areal density and damage area per impact energy are more meaningful than unnormalised peak load.

Table 1. Qualitative comparison of the reinforcing fibres and its implications for laminate design.

Attribute	PAN-based carbon fibre	Kevlar K29	Hybrid-design implication
Density	~1.75-1.85 g cm-3	~1.44 g cm-3	Aramid can reduce areal mass when substituted judiciously.
Axial modulus	High to very high	Moderate	Carbon should occupy stiffness-critical outer plies.
Tensile strain to failure	Relatively low	Higher	Aramid can bridge cracks after carbon damage initiates.
Compression	Strong but microbuckling-sensitive	Comparatively weak	Avoid Kevlar-dominated compressive faces in stiffness-critical laminates.
Impact response	Brittle damage and delamination	High energy absorption and fibrillation	Use aramid near impact-prone regions or as a core/interleaf.
Moisture/interface	Generally manageable with sizing	More moisture-sensitive and difficult to bond	Surface treatment and resin selection are critical.
Electrical conductivity	Conductive	Insulating	Hybridisation can create anisotropic multifunctional behaviour.

4. Hybrid Architectures

4.1 Interply Hybridisation

Interply laminates use discrete carbon and Kevlar plies. They are compatible with conventional lay-up, prepreg and infusion routes, and their stacking sequence can be tailored using classical laminate theory. Carbon skins with a Kevlar-rich core commonly provide a favourable balance: high-modulus carbon plies carry bending stresses at the surfaces, while internal aramid plies impede delamination growth and absorb impact energy. Experimental studies on CFRP/Kevlar sandwich-type laminates have reported improved impact-damage resistance and compression-after-impact tolerance relative to monolithic CFRP [13, 18].

Alternating carbon and aramid plies increase the number of hybrid interfaces. This can distribute damage but also creates more sites for interfacial shear and resin-rich regions. Closely alternating thin plies may suppress unstable crack growth, whereas thick dissimilar blocks tend to localise stress at a small number of interfaces. The optimum degree of dispersion therefore depends on matrix toughness and interface quality.

4.2 Intraply Woven Hybrids

Intraply fabrics combine carbon and aramid tows within the same textile layer. They reduce the scale of heterogeneity and can spread impact damage over a wider region. Quasi-isotropic intraply fabrics are attractive for thin panels and complex shapes, but local response depends on towpath, crimp, impact location and the carbon-to-aramid distribution within the weave [14, 19]. Because warp and weft directions can contain different fibre fractions, conventional homogenised lamina models may not capture yarn-level load transfer or local splitting. Intraply systems can also improve manufacturing convenience by handling both fibres as a single fabric. However, differential wetting and tow permeability may create nonuniform resin distribution. Accurate quality control therefore requires microstructural inspection rather than bulk fibre-volume measurement alone.

4.3 Braided, Stitched and Three-Dimensional Architectures

Braiding and three-dimensional weaving introduce through-thickness reinforcement and mechanical interlocking. These architectures can suppress delamination and improve penetration resistance, but they increase fibre waviness and may reduce in-plane modulus. Carbon/Kevlar hybrid braids are especially promising for tubular members, leading edges, protective shells and energy-absorbing substructures. Recent work has examined their quasi-static indentation and low-velocity impact damage at the mesoscale [20]. Stitching or z pinning can raise interlaminar fracture resistance, but the insertion process may break carbon fibres or create resin pockets. For thin aerospace skins, the weight and surface-quality penalties must be evaluated against the improvement in damage tolerance.

5. Manufacturing Routes and Process-Induced Quality

5.1 Hand Lay-Up and Vacuum Bagging

Hand lay-up followed by vacuum bagging is common in exploratory studies because it is inexpensive and permits rapid variation of stacking sequence. Its limitations include operator dependence, resin-content scatter, entrapped air, waviness and thickness variation. Such defects can obscure the intrinsic hybrid effect. Results from hand-laminated coupons should therefore report constituent areal weight, resin mass fraction, vacuum level, cure schedule and measured void content.

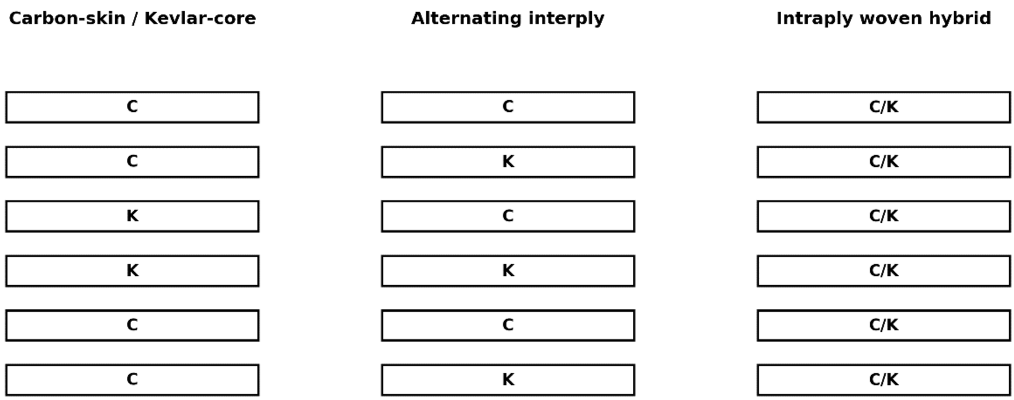

Figure 2. Representative carbon/Kevlar hybrid architectures. C denotes carbon plies and K denotes Kevlar plies.

5.2 Vacuum-Assisted Resin Infusion and Resin-Transfer Moulding

Vacuum-assisted resin infusion and resin-transfer moulding provide improved scalability and more reproducible fibre volume. Hybrid fabrics can nevertheless show complex permeability because carbon and aramid tows compact differently and aramid can retain moisture. Flow-front race tracking, dry spots and local resin-rich zones are important risks. Process simulation and embedded pressure or dielectric sensors can help optimise inlet placement and cure progression.

5.3 Prepreg and Autoclave Processing

Prepreg-autoclave curing remains the benchmark for primary aerospace structures because controlled resin content, debulking and elevated pressure can minimise voids. The approach offers superior consistency but at high capital, energy and tooling cost. Carbon and Kevlar prepregs may require compatible tack, drape and cure kinetics; otherwise, interfaces between unlike prepreg systems can become weak planes. Co-curing a common matrix system is generally preferable to combining independently formulated prepregs.

5.4 Out-Of-Autoclave, Thermoplastic and Additive Routes

Out-of-autoclave prepregs, compression moulding and thermoplastic consolidation are attractive for higher-rate production and improved repairability. Thermoplastic matrices can provide greater impact toughness and recyclability, but high melt viscosity complicates impregnation of dense aramid textiles. Automated fibre placement of mixed tows offers spatially graded hybridisation, yet tow steering, gaps, overlaps and differential compaction need careful control.

Continuous-fibre additive manufacturing is emerging for complex lightweight structures, but current void levels, fibre steering constraints, surface finish and certification maturity remain below those of aerospace prepreg systems [21].

Table 2. Manufacturing options for carbon/Kevlar hybrid aerospace composites.

Process	Strengths	Principal risks	Best-fit application
Hand lay-up + vacuum bag	Low tooling cost; flexible stacking studies	High variability; voids; resin-rich zones	Coupon screening and prototypes
Vacuum infusion / VARTM	Large parts; moderate cost; closed processing	Permeability mismatch; dry spots	Panels, fairings, UAV structures
RTM	Repeatability; two-sided finish; automation potential	Tool cost; flow complexity	Medium-volume shells and frames
Prepreg-autoclave	Lowest void content; aerospace pedigree	High cost and energy use	Primary load-bearing structures
Out-of-autoclave prepreg	Reduced infrastructure; scalable	Moisture and vacuum sensitivity	Secondary structures and large panels
Thermoplastic consolidation	High toughness; weldability; recyclability	High processing temperature and viscosity	Rapid-cycle, repairable structures
Braiding / 3D weaving	Near-net shape; through-thickness reinforcement	Waviness; complex modelling	Tubes, leading edges, crash structures

6. Static Mechanical Response

6.1 Tensile Behaviour

Axial tensile response is usually governed by carbon-fibre orientation and volume fraction until carbon failure begins. Aramid plies can delay complete separation by bridging cracked carbon regions, producing a more progressive post-peak response. The apparent tensile hybrid effect is strongest when constituent failure strains are sufficiently different for aramid to remain intact after carbon fracture, but too large a mismatch can create abrupt stress transfer and delamination. Open-hole tensile strength is a particularly relevant metric because aerospace laminates contain fastener holes and cut-outs. A Kevlar core can reduce notch sensitivity by redistributing stress and increasing fracture work. Recent carbon/Kevlar sandwich studies reported improved open-hole toughness relative to monolithic CFRP, although stiffness remains carbon-dominated [22].

6.2 Flexural and Compressive Behaviour

Flexural performance is highly sensitive to ply location. Placing carbon at the outer surfaces maximises bending stiffness because surface plies experience the largest tensile and compressive stresses. Kevlar on the compression face can lower flexural strength through fibre microbuckling, while Kevlar in the mid-plane contributes less to stiffness but can impede internal cracking. This explains why carbon-skin/Kevlar-core arrangements are repeatedly favoured for structural panels.

Compression is often the limiting property of carbon/aramid hybrids. Aramid's low compressive strength and the presence of impact-induced delamination can trigger premature instability. Compression-after-impact testing is therefore more informative than unnotched compression alone for aerospace qualification.

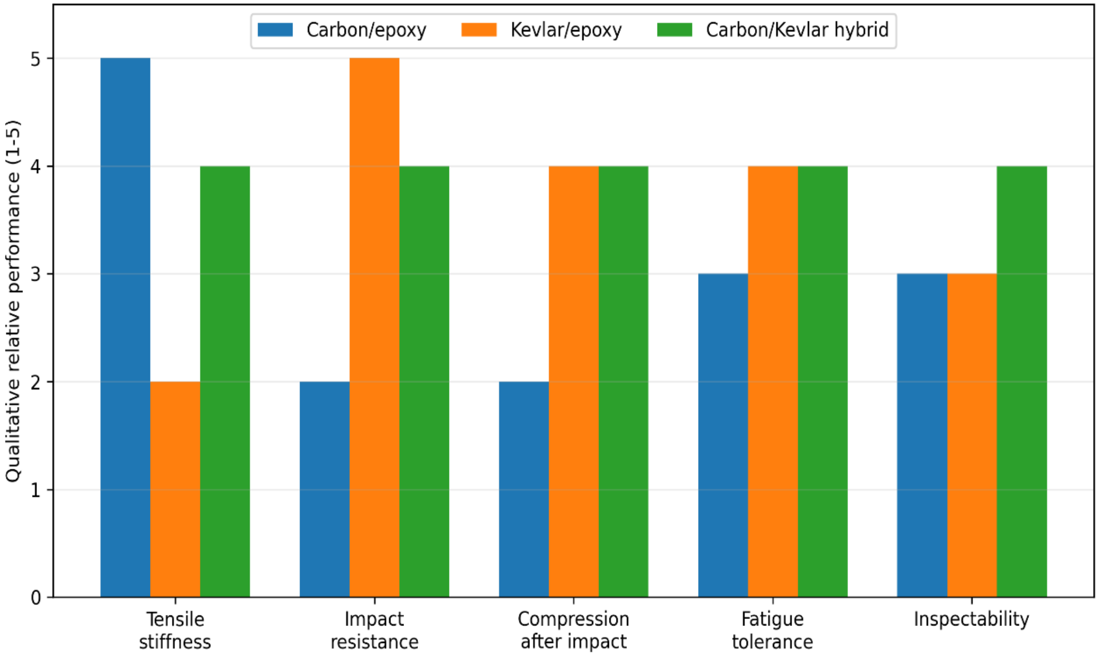

Figure 3. Qualitative performance trade-off among monolithic carbon/epoxy, Kevlar/epoxy and a well-designed carbon/Kevlar hybrid. The ratings are conceptual rather than pooled experimental values.

6.3 Interlaminar Fracture and Interface Control

Mode I and Mode II fracture toughness govern delamination initiation and growth. Aramid fibres can bridge crack faces and increase fracture work, but weak aramid-matrix adhesion may cause interfacial debonding rather than cohesive matrix failure.Mixed-mode studies on plain and woven carbon/Kevlar systems indicate that architecture and yarn interlacing strongly influence crack path [23].

Interface modification should be evaluated with both strength and fracture metrics. A treatment that raises short-beam shear strength may not necessarily improve long-crack resistance. Fractography is essential to distinguish fibre pull-out, cohesive resin failure, sizing failure and interfacial debonding.

7. Impact, Ballistic Response and Residual Strength

7.1 Low-velocity impact

Low-velocity impact creates a complex sequence of contact indentation, matrix cracking, delamination, fibre fracture and back-face deformation. CFRP can sustain a small surface dent while developing a large hidden delamination area. Aramid-rich layers deform more visibly and absorb energy through yarn stretching and fibrillation. In a hybrid, the challenge is to exploit aramid dissipation without sacrificing carbon-supported load transfer.

Stacking sequence controls peak force, contact duration, absorbed energy and damage area. Carbon outer plies generally increase peak load and reduce global deflection, while Kevlar outer plies reduce penetration risk and spread damage. Hybrid-ply intercalation can alter the sequence of damage initiation and improve low-velocity impact resistance [15]. Studies on carbon/aramid woven laminates further show that impact response should be coupled with compression-after-impact rather than assessed only from absorbed energy [16].

7.2 Compression and Bending After Impact

Residual strength is a safety-critical metric because damage that appears tolerable under impact may cause severe instability under subsequent compression. Kevlar-core CFRP laminates have demonstrated improved damage resistance and tolerance under impact followed by compression [13]. Under bending-after-impact, carbon/Kevlar hybrids can redistribute load across intact plies, but the improvement depends on whether delamination separates the carbon load paths from the aramid energy-absorbing region [17].

A design that maximises absorbed energy is not necessarily optimal for residual strength. Excessive global deformation can absorb energy while leaving large delaminations. Aerospace optimisation should therefore combine absorbed energy, damage area, dent depth, residual compressive strength and failure mode.

7.3 High-Velocity and Ballistic Loading

At high velocity, local penetration, shear plugging, yarn rupture and projectile-fibre friction become dominant. Kevlar is effective for tensile membrane action and projectile arrest, while carbon can increase front-face rigidity and spread load. Hybrid ratio, intraply texture and impact position relative to tow crossover determine the synergy. The resulting architecture may be relevant to rotorcraft floors, engine-containment features, leading edges and protective UAV skins, but ballistic optimisation should not be transferred directly to primary structural design because loading rates and failure modes differ.

8. Fatigue, Creep and Environmental Durability

8.1 Fatigue Damage Evolution

Composite fatigue develops through distributed matrix cracking, interface debonding, delamination, fibre breakage and final instability. Hybridisation may retard crack growth by interrupting continuous brittle carbon paths and providing aramid bridging. A broad review of hybrid-composite fatigue concluded that improvements are possible but strongly dependent on constituent combination, stress ratio, sequence and failure criterion [24].

For carbon/Kevlar laminates, stiffness degradation, acoustic-emission activity and residual strength should be reported together. S-N curves alone can conceal changes in damage mode. Variable-amplitude spectra representative of gusts, manoeuvres and pressurisation are more relevant than constant-amplitude tension-tension tests.

8.2 Moisture and Temperature

Aramid fibres can absorb moisture, and the fibre-matrix interface may deteriorate during hygrothermal exposure. Moisture plasticises many epoxies, reduces glass-transition temperature and changes interlaminar fracture behaviour. Carbon fibres are less moisture-sensitive, but galvanic interaction becomes a concern when conductive carbon contacts aluminium in the presence of an electrolyte. Hybrid structures require edge sealing, compatible primers and isolation layers. Elevated temperature reduces matrix stiffness and can lower the compressive stability of both carbon and aramid laminates. At sub-zero temperature, matrix brittleness and thermal-expansion mismatch may increase cracking. Qualification should therefore include combined moisture-temperature-fatigue exposure rather than independent environmental tests.

8.3 Fire, Smoke, Toxicity and Lightning-Strike Considerations

Carbon/Kevlar hybrids do not inherently solve fire-smoke-toxicity requirements. Matrix chemistry dominates heat release and smoke generation. Carbon provides some electrical conduction, whereas Kevlar is insulating; hybridisation can therefore produce nonuniform current pathways under lightning strike. Expanded metal foils, conductive veils or nano-modified surface layers may still be needed, with associated weight and impact on repair.

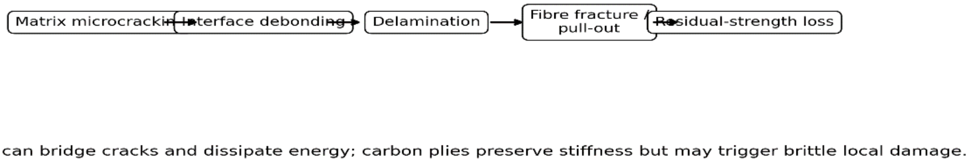

Figure 4. Typical damage progression in a carbon/Kevlar hybrid laminate under repeated or impact-assisted loading.

9. Failure Mechanisms and Diagnostic Methods

The dominant failure mechanisms are matrix microcracking, fibre-matrix debonding, delamination, carbon-fibre fracture, aramid fibrillation and pull-out, compressive kink bands and bearing damage around fasteners. The sequence depends on loading mode. Carbon-dominated regions fail abruptly, whereas aramid-dominated regions usually show progressive deformation. Hybrid interfaces can either arrest a crack or redirect it into a weak interlaminar path.

Optical microscopy and scanning electron microscopy remain essential for post-mortem interpretation, but they capture only final damage. X-ray computed tomography, ultrasonic C-scan, thermography, acoustic emission and digital image correlation provide complementary information on internal delamination and strain localisation. No single non-destructive method detects every damage type; robust structural assessment requires sensor fusion and calibration against destructive sectioning [25].

For certification, detectability matters as much as damage resistance. A material that develops a larger but shallow and easily detected damage zone may be safer than one that develops a small barely visible delamination with severe residual-strength loss. Inspection thresholds should therefore be integrated with laminate design.

10. Modelling and Multi-Scale Design

10.1 Classical and Analytical Approaches

Classical laminate theory is useful for in-plane stiffness and first-pass stacking optimisation but cannot capture nonlinear impact, progressive damage or yarn-scale heterogeneity. Rule-of-mixtures and Halpin-Tsai formulations provide constituent bounds, yet they should not be interpreted as predictions of hybrid damage tolerance. Analytical models require calibrated failure criteria for carbon, aramid, matrix and interfaces.

10.2 Finite-Element Progressive Damage

Continuum damage mechanics models commonly use Hashin-, Puck- or LaRC-type criteria for intralaminar failure, combined with cohesive elements for delamination. Separate parameters are needed for carbon and aramid plies because their tensile and compressive damage evolution differs markedly. Model credibility depends on mesh-objectivity, fracture-energy regularisation, contact treatment and independent validation against force-time response, damage area and residual strength.

Mesoscale models of woven or braided hybrids explicitly represent yarns and resin pockets. They can resolve impact-location effects but are computationally expensive. Reduced-order homogenisation and sub-modelling offer a practical compromise for structural components.

10.3 Optimisation and Uncertainty

Hybrid laminate optimisation is inherently multi-objective. Objectives may include mass, stiffness, impact energy, residual strength, cost and inspectability, subject to manufacturing rules and ply-contiguity constraints. Genetic algorithms, surrogate models and Bayesian optimisation are increasingly useful. However, deterministic optimisation can select fragile designs if scatter in fibre strength, void content and interface toughness is ignored. Reliability-based design should incorporate manufacturing variability and environmental knock-down factors.

11. Aerospace Applications and Design Framework

Potential applications include fuselage and fairing panels, access doors, control surfaces, radomes, UAV skins, rotorcraft interiors, cargo liners, protective leading edges and secondary load-bearing members. Primary structures require a stronger evidence base because certification demands traceable material allowables, process control, damage tolerance, inspection procedures and repair substantiation.

A practical design sequence is: define the dominant mission loads; identify whether stiffness, impact, fatigue or penetration is limiting; select carbon and aramid functions; choose interply, intraply or 3D architecture; select a common matrix and compatible sizing; define process controls; test impact and residual strength; quantify environmental knock-downs; validate numerical models; and establish inspection and repair limits.

Carbon skins with a Kevlar core are well suited to bending-dominated panels requiring retained stiffness after impact. Kevlar-rich outer layers are more suitable where penetration resistance and visible damage are dominant. Intraply textiles are attractive for complex shells and distributed impact resistance, while braided architectures suit tubes and curved energy-absorbing members.

Table 3. Architecture-selection framework for representative aerospace requirements.

Design requirement	Preferred architecture tendency	Critical validation metric	Main caution
Maximum bending stiffness	Carbon-rich outer plies	Flexural modulus and buckling	Brittle impact damage
Low-velocity impact tolerance	Kevlar core/interleaf or hybrid woven ply	Damage area + CAI	Thickness and resin-content effects
Penetration resistance	Kevlar-rich impact face or intraply hybrid	Perforation energy and back-face deflection	Reduced compressive stiffness
Fatigue crack retardation	Dispersed thin aramid plies	Stiffness loss and residual strength	Hybrid-interface delamination
Complex tubular geometry	Braided/3D hybrid	Crush energy and torsion	Fibre waviness
Electrical multifunctionality	Carbon network retained	Conductivity and lightning test	Kevlar interrupts current paths
Repairable high-rate part	Thermoplastic hybrid	Weld/repair strength	Impregnation difficulty

12. Research Gaps and Future Directions

First, the field needs standardised reporting. Many studies omit fibre volume fraction, areal density, void content, cure cycle or constituent grades, making cross-study comparison unreliable. Test programmes should report both absolute and mass-normalised performance.

Second, phase-space coverage is limited. Most experiments vary only one stacking sequence or impact energy. Design-of-experiments approaches should jointly vary fibre ratio, ply thickness, weave, matrix toughness and impact condition.

Third, fatigue and environment remain underdeveloped. Long-duration variable-amplitude fatigue after impact, combined with moisture and temperature cycling, is essential for aerospace relevance.

Fourth, multi-scale models require better validation. Simulations should reproduce not only peak force but also damage morphology, absorbed energy, delamination growth and residual strength across multiple geometries.

Fifth, manufacturing and inspection should be integrated. In-situ cure monitoring, automated defect detection and structural-health-monitoring networks can reduce certification uncertainty.

Sixth, sustainability must be addressed. Thermoplastic matrices, recycled carbon fibre, recoverable aramid streams and low-energy out-of-autoclave processing should be evaluated using life-cycle and repairability metrics rather than mechanical performance alone.

Finally, full-scale demonstrators are needed. Coupon success should progress through sub-element tests, joints, curved panels and representative aerospace loading before claims of structural readiness are made.

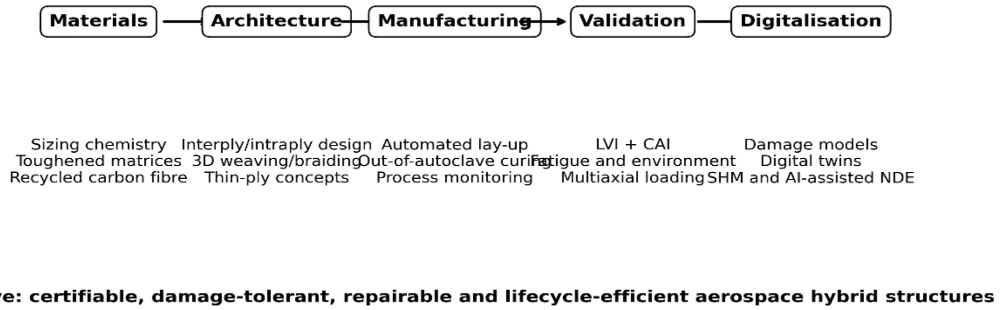

Figure 5. Research and technology roadmap for certifiable carbon/Kevlar aerospace hybrid structures.

13. Conclusions

Kevlar K29/PAN-based carbon-fibre hybrid composites can provide a useful combination of stiffness, low mass, impact resistance and progressive failure, but the benefit depends on architecture and processing rather than fibre combination alone. Carbon-rich surface plies generally maximise flexural rigidity and load-bearing efficiency, while Kevlar-rich internal plies improve energy dissipation, crack bridging and impact-damage tolerance. Alternating interply arrangements can distribute damage but also multiply weak interfaces; intraply and braided hybrids offer more distributed reinforcement at the cost of manufacturing and modelling complexity.

The most important design insight is that peak impact energy absorption should not be used as a stand-alone selection criterion. Aerospace qualification must consider damage area, dent depth, compression or bending after impact, fatigue degradation, environmental durability and inspectability. Interface quality is central because aramid's moisture sensitivity and limited adhesion can convert a potentially tough hybrid into a delamination-prone laminate.

Future Q2-level research should combine rigorous process characterisation, multi-objective architecture optimisation, mixed-mode fracture testing, variable-amplitude fatigue, hygrothermal exposure, validated progressive-damage modelling and non-destructive inspection. Thermoplastic matrices, thin-ply dispersion, three-dimensional textiles and embedded sensing are promising directions. With these advances, carbon/Kevlar hybrids can move from coupon-scale demonstrations toward certifiable secondary and selected primary aerospace structures.

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