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Review

A Review of Polymer Composites and Adhesives for Aircraft Landing Gear Applications

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Abstract

This review paper explores the transformative potential of polymer composites and adhesives in reducing the weight of aircraft landing gear, thereby improving fuel efficiency and lowering emissions. The replacement of conventional metallic materials and mechanical fastenings with advanced thermoset/thermoplastic composites and adhesives can significantly enhance durability and performance in demanding operational environments. Unlike traditional fastening methods, the structural adhesives eliminate the weight penalties associated with mechanical fasteners, offering a lighter and more reliable solution that meets the rigorous demands of modern aerospace engineering. Furthermore, the review highlights a variety of manufacturing techniques and innovative materials, including bio-based polymers, self-healing materials, noobed composites, helicoid composites, and hybrid composites. The use of thermosets and vitrimers in adhesive bonding are presented, illustrating their ability to create robust and durable joints that enhance the structural integrity of landing gear systems. The paper also addresses current challenges, including recycling limitations and high material costs. Sustainability considerations, including the integration of self-healing materials, structural health monitoring systems, and circular economy principles, are discussed as essential for aligning the aerospace sector with global climate goals.

Keywords: landing gear; composite; adhesive; structural integrity; sustainability

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Academic Editor: Andrea Da-Ronch

Received: 11 July 2025
Revised: 25 August 2025
Accepted: 1 September 2025
Published: 2 September 2025

Citation: Caglar, H.; Ayre, D.; Mills, A.; Xu, Y.; Skote, M. A Review of Polymer Composites and Adhesives for Aircraft Landing Gear Applications. *Aerospace* **2025**, *12*, 794. https://doi.org/10.3390/aerospace12090794

1. Introduction

The aerospace industry is consistently driven to reduce aircraft weight, primarily to enhance fuel efficiency and decrease emissions. Weight reduction can be achieved through various strategies, including the design of more lightweight components, the utilisation of polymer composites, the adoption of adhesive bonding to replace mechanical fasteners, and a shift in design philosophy from safe-life to damage-tolerant methodologies. Most of an aircraft's value is concentrated in a few key components, such as engines, landing gear, and avionics [1]. Landing gear contributes 3–5% of an aircraft's take-off weight, making weight reduction essential for performance and efficiency.

The aerospace industry has increasingly adopted composites to produce lighter and more fuel-efficient aircraft. Figure 1 [2] illustrates this trend, with wide-body models like the Boeing 787 and Airbus A350 achieving over 50% composite composition by weight. Compared to the Boeing 767, the 787 delivers 20% greater fuel efficiency, 5% lower noise, and 30% reduced maintenance costs, due to strategic application of advanced lightweight materials such as composites and titanium [3]. While narrow-body aircraft, like the C Series (known as the Airbus A220) and MC-21, are also adopting composites, they lag behind wide-body models in terms of integration.

Adhesive bonding is emerging as a promising alternative to traditional mechanical fasteners in semi-structural aerospace applications and as a secondary load-bearing element for structural applications. This technology enables lightweight designs, uniform load distribution, and excellent resistance to environmental challenges. Additionally, adhesive bonding addresses the limitations of conventional joining methods by allowing the seamless joining of dissimilar materials, reducing stress concentrations, and enhancing structural performance. These benefits make it a valuable solution for improving durability and reliability in demanding aerospace environments, though its long-term performance in the most demanding environments continues to be evaluated [4].

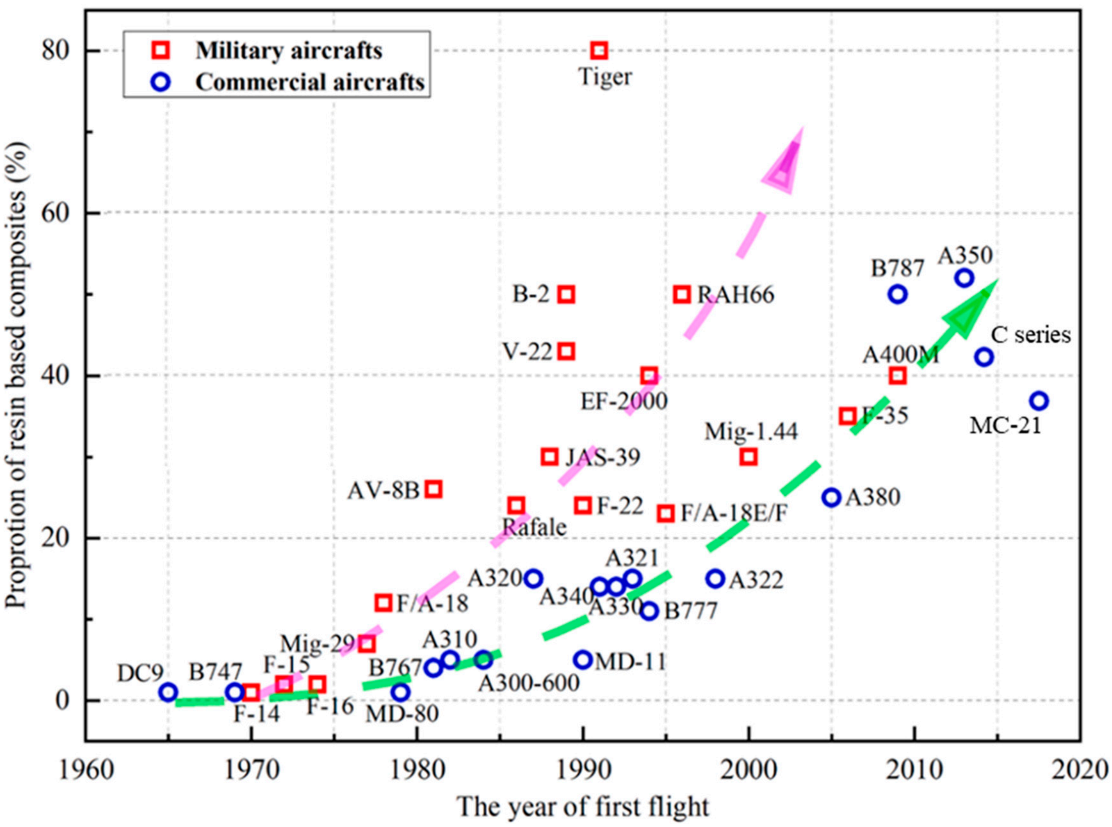


Figure 1. Composite composition of commercial aircraft by structural weight since 1970 (modified by combining the information from both references) [2,5].

At the same time, growing environmental concerns regarding the increase in plastic production, including materials used in composites, highlight the importance of developing efficient recycling methods for both fibre reinforcements and polymer matrices, though effective recycling remains challenging, as each material component presents unique technical and economic barriers [6].

Jemiolo [7] compares the global warming potential of different aircraft models in 2015 and 2050. Operational cycles, including take-off, climb, cruise, and descent, dominate the total emissions for all aircraft types. This highlights the importance of operational efficiency improvements and lightweighting strategies to reduce emissions. Projections show the continued significance of operational emissions by 2050, despite advancements in technology. The ecoinvent dataset [8] for airport construction was used, which accounts for the entire life cycle of Zurich Airport, including construction, operation, and end-of-life [9].

A key issue is that around 85% of composite structures are not recycled but instead disposed of in landfill, exacerbating environmental concerns [10]. Rivets, while structurally reliable, are costly and time-consuming to remove, often rendering carbon fibre components uneconomical to recycle [11]. Rivetless joining solutions, such as structural adhesives, offer a more sustainable alternative. By eliminating mechanical fasteners, they enable easier disassembly and recovery of valuable materials, thereby reducing waste and lowering the overall carbon footprint of aerospace components.

Sustainability in composites is increasingly necessary for the aerospace industry, with a focus on lightweighting, recycling, and circular economy principles. While composites offer fuel savings and lower life-cycle emissions, challenges remain in end-of-life disposal and recycling capacity. Advancements in Design for Manufacturing, Assembly, and Disassembly (DfMAD), adhesive bonding for rivetless assembly, and bio-based alternatives will be key to reducing environmental impact. As composite usage grows, innovations in material recovery and sustainable manufacturing will ensure they remain a cornerstone of greener aviation.

In 2023, there was an increase in non-fatal aircraft accidents, with 10 out of 18 cases involving substantial damage, particularly to landing gear systems [12]. Among the most notable incidents were wheel explosions, nose-wheel separations, and landing gear damage during touchdown. Failures in the landing gear emerged as a leading cause, alongside mid-air and ground collisions. Research by Wang et al. [13] found that drop height of the aircraft landing gear, which is the distance from the bottom of the tyre to the impact platform, is the most influential factor affecting its load-bearing capacity. It also significantly impacts the vertical impact loads and the peak, fluctuation and action time of the longitudinal and lateral impact loads. This reflects the importance of designing systems that can effectively absorb and distribute impact forces to enhance safety and durability.

Airbus' commitment to sustainability is reflected in its research into dustless and rivetless joining, disassembly, dismantling, and recycling techniques [14]. Dustless and rivetless joining supports lightweighting while eliminating harmful dust-generating processes, reducing environmental impact during manufacturing. Additionally, improved disassembly and recycling techniques enable efficient material recovery. These efforts highlight the necessity of DfMAD. According to the Aerospace Joining Technology Roadmap by the Aerospace Technology Institute (ATI) [15], adhesives and sealants will be central for joining primary structures, but they face certification challenges.

2. Polymer Composites Used in Landing Gear

In the aerospace industry, high-strength metastable β-titanium alloys, such as Ti-5553 (Ti–5Al–5Mo–5V–3Cr), are used for landing gear systems by companies such as Liebherr-Aerospace Lindenberg GmbH [16]. However, their manufacturing is expensive due to complex geometries, high tooling costs, and material waste. To address this, research has explored additive manufacturing techniques, such as depositing cost-effective Ti-64 (Ti–6Al–4V) onto forged Ti-5553 substrates [17]. While these titanium alloys show promise for weight reduction compared to traditional 300M steel, they still have a comparable specific modulus but 40% lower specific strength, limiting their weight-saving potential as listed in Table 1. Given this trade-off, manufacturers are likely to choose cost-effective, well-established materials such as 300M steel, where they have greater experience and proven reliability. This balance of performance and cost-effectiveness highlights the need for continued innovation in landing gear materials and manufacturing processes.

Table 1. Comparison between traditional materials, synthetic fibres, CF and CFRP [5,18–21].

Type	Material	Tensile Modulus (GPa)	Tensile Strength (MPa)	Density (g/cm^3)	Specific Modulus (GPa/g/cm^3)	Specific Strength (MPa/g/cm^3)
Traditional materials	45 Steel	210	600	7.85	27	76
	300M Steel	205	2040	7.87	26	259
	Ferrium® S53	205	1990	7.97	26	250
	Ferrium® M54	196	2020	7.97	25	253
	Aermet® 100	196	1970	7.84	25	251
	Ti-6Al-4V	117	971	4.5	26	216
Synthetic fibres	E-Glass fibre	70–76	3100–3800	2.5–2.6	29	1102
	Aramid fibre	124	3380	1.44	86	993
	T300	230	3530	1.76	131	2006
	T700	230	4900	1.80	128	2722
	T800	294	5490	1.81	162	3033
Resin-based composites [1]	Glass fibre/epoxy	48	1245	2.00	24	623
	Aramid fibre/epoxy	78.4	1373	1.40	56	981
	T300/epoxy	128	1760	1.60	81	1100
	T700/epoxy	130	2100	1.60	81	1310
	T800/epoxy	154	2950	1.6	96	1814
	T800/PEEK	155	2200	1.57	98	1401

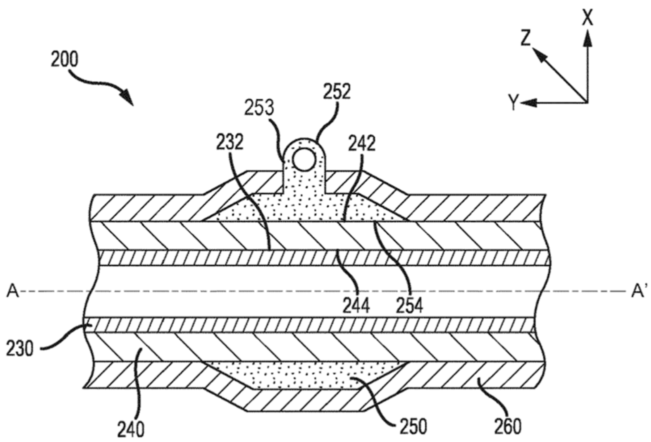
[1] The resin-based composites data is based on a 100% unidirectional (UD) layup, meaning the properties are around 100–200% higher than what would typically be observed in an engineered component.

However, carbon fibre-reinforced polymers (CFRPs) present a compelling alternative, offering higher specific strength and stiffness alongside significant weight reduction opportunities. As shown in Table 1, CFRPs outperform both steel and titanium alloys in terms of specific strength and stiffness, making them an attractive option for next generation landing gear designs. Their lower density further enhances fuel efficiency and reduces overall aircraft weight; however, their heterogeneous and anisotropic nature often necessitates component redesign to fully exploit their mechanical advantages. For landing gear applications, this includes overcoming challenges related to damage detection, impact tolerance, and reliable joining methods. Ensuring consistent performance under high cyclic loads and harsh environmental conditions also remains critical, requiring advancements in structural health monitoring and repair strategies.

Landing gear accounts for approximately 3–5% of an aircraft's take-off weight. As the primary load-bearing system during taxiing, take-off, and landing, it is a critical component for both safety and performance. But strengthening of the adjacent/surrounding structure increases this weight significantly. While reducing the mass of the landing gear directly lowers the aircraft's overall weight, the extent to which this enables a reduction in structural reinforcement—particularly attached components and attachment points—may be limited. Any potential weight savings in these areas would depend on design constraints and load requirements. This cascading benefit highlights the wider impact of landing gear optimisation on overall aircraft efficiency. The Composite Material Applications in Aerospace report by ATI [22] shows a substantial growth in the market for composite landing gear components, rising from £2.6 billion (2017–2019) to £5.2 billion (2020–2024). Though a slight decline to £4.4 billion (2025–2029) is expected, the market is projected to reach £10.3 billion by 2030–2035. Composites offer corrosion resistance, shock absorption, and weight reduction, making them a candidate for advanced landing gear designs that align with sustainability goals. Airbus's plan to double production rates of key aircraft models by 2025 reflect the increasing demand for lightweight components [14]. As production scales up, Airbus continues to prioritise weight reduction to enhance fuel efficiency and performance, further driving the need for advanced lightweight materials.

GKN Fokker Landing Gear has pioneered composite landing gear technology, developing carbon fibre-reinforced polymer (CFRP) drag stay braces for the F-35 Lightning II [23]. These advancements demonstrated the feasibility of composite materials for drag braces and other landing gear components [24]. Additionally, in the HECOLAG project, NLR and GKN Fokker collaborated with Safran Landing Systems to develop a CFRP lower side stay for an electrified main landing gear system [25]. The INNOTOOL 4.0 subproject, led by GKN Fokker Landing Gear, advanced automated production of CFRP landing gear structures using resin transfer moulding (RTM) [23]. This project introduced sensor-integrated tooling, which enabled smaller, lighter tools that facilitate faster production cycles, easier handling, lower energy consumption, increased automation, and intelligent Industry 4.0 process control.

Traditionally, landing gear structural components are composed entirely of metal, which, while robust, adds considerable weight. The use of polymer-matrix fibre-reinforced composites offers a significant weight reduction advantage, but these materials often struggle with accommodating concentrated internal loads. A related patent [26] outlines a landing gear configuration featuring a first composite layer designed with a cylindrical geometry. Surrounding part of this composite layer is a metallic ring, which includes both an inner and outer surface as can be seen in Figure 2. The inner surface of the ring is in direct contact with the composite layer, while the outer surface connects to a metallic tab extending outward. A second composite layer partially encases both the metallic ring and the first composite layer, ensuring direct contact between the ring's outer surface and the second composite layer. This hybrid design addresses one of the key challenges in composite-based landing gear systems, efficiently transferring localised loads, by integrating metallic elements into load-critical areas. The present configuration exemplifies an engineered solution that leverages the lightweight benefits of composites while using metallic components to enhance load distribution and structural integrity.



200 – landing gear arrangement	230 – metallic liner
232 – outer surface	240 – first composite layer
242 – outer surface	244 – inner surface
250 – load transfer member	252 – connecting tab
253 – lug	254 – inner surface
260 – second composite layer	

Figure 2. An axial cross-section view of a landing gear arrangement, in accordance with various embodiments [26].

3. Role of Adhesives in Enhancing Landing Gear Performance

In today's composite primary structures, fasteners are employed due to certification requirements. Certifying bonded composite primary structures requires thorough validation of manufacturing and the development of specific regulatory regimes, as pursued by major aerospace companies such as Boeing, Airbus, and Lockheed Martin [27]. Increasing the reliability of these structures involves improving design, process control, and quality assurance, including exploring redundant load paths and advanced surface preparation techniques. The goal is to achieve reliable and repeatable bonding processes to enable wider adoption in composite airframes.

Still, adhesive bonding is an important technique in modern aircraft manufacturing, providing significant advantages over traditional mechanical fasteners. It is used in components such as wing boxes and fuselage panels mainly for stiffener attachment, enhancing structural integrity and performance [28]. By reducing corrosion, fatigue, and stress concentrations, bonded joints can offer up to 20% more strength than riveted ones. Adhesives also save weight, simplify assembly, and enable innovative designs without pre-drilled holes. This technique creates lighter, stronger, and more efficient structures, addressing aviation's demands for performance and sustainability.

Structural adhesives, particularly epoxy adhesives, play a critical role in the repair of composite aircraft structures [29], offering strong, lightweight bonding without the need for mechanical fasteners. They help restore structural integrity while minimising added weight and preserving aerodynamic performance.

The ATI's Aerospace Joining Technologies Roadmap [15] outlines key advancements in aerospace joining methods as follows:

- Manufacturers aim to eliminate fasteners through welding and adhesive bonding while developing certifiable techniques like co-curing, friction joining, and refill friction stir spot welding (FSSW).
- Research into self-healing adhesive joints and sustainable consumables for joining processes is prioritised.
- Efforts focus on improving NDT methods for inspecting bonded interfaces and leveraging artificial intelligence (AI) to optimise joining processes and ensure quality.
- Sustainability is a major trend, with autogenous welding emerging as a preferable option to minimise contamination in recycling metallic structures.
- Digital twins are also highlighted for simulating manufacturing operations, enabling process optimisation and enhanced production efficiency.

Adhesive bonding and co-consolidation techniques are two principal approaches for thermoplastic composites (TPCs) [30]. Co-consolidation is considered another method for joining TPC joints, which is similar to co-curing for joining thermoset composite (TSC) joints. For co-curing, the two composite adherends and the adhesive layer were cured at the same time. For co-bonding, one side of the composite adherend and the adhesive were cured onto a composite adherend that had already been cured. Co-consolidation achieves the highest joint strengths by consolidating composite layers and adhesives simultaneously, making it ideal for high-stress applications. However, it is less efficient in terms of processing time. Secondary bonding and co-bonding, while offering lower strength, are quicker and more cost-effective, particularly for moderate performance requirements. These methods balance strength and efficiency depending on the specific application needs.

Table 2 summarises the comparative performance of bonded, riveted, and hybrid joints based on the findings of Zhang et al. [31]. Bonded joints, while offering linear stiffness, suffer from abrupt failure and complete loss of load-bearing capacity upon adhesive fracture. Riveted joints provide residual strength of ~5 kN after failure but are limited by local CFRP damage around holes. Hybrid joints combine the benefits of both methods, achieving higher peak loads, progressive failure through load sharing, and superior energy absorption. These attributes underline their potential suitability for landing gear applications, where both strength and damage tolerance are critical.

Table 2. Comparison of bonded, riveted, and hybrid joints (adapted from Zhang et al. [31].).

Joint Type	Behaviour/Stiffness	Failure Load/Capacity	Failure Process/Mode	Performance Outcome
Bonded joint	Linear stiffness throughout loading	Complete load loss after adhesive fracture	Adhesive fracture	Lowest strength; lowest energy absorption
Riveted joint	Nonlinear at ~0.5–1.0 mm due to CFRP hole damage	Residual capacity ~5 kN post-failure	CFRP hole damage followed by rivet-only load bearing	Moderate strength; moderate energy absorption
Hybrid joint	Initial stiffness and peak load decrease with increasing bond line thickness; linear beyond ~1.0 mm until failure	Higher peak load than bonded or riveted joints; post-peak drops to ~5 kN (rivet-only behaviour)	(i) Adhesive + rivet share load; (ii) progressive adhesive fracture; (iii) rivet bears load alone	Superior strength and energy absorption

The performance of adhesively bonded joints is highly dependent on how the composite substrates are prepared, as this impacts the surface morphology and topography, the interfacial chemical properties, and the mechanical characteristics of the adhesive–adherend interface. Yudhanto et al. [32] review key composite surface preparation methods, though environmental durability—particularly against moisture, hydraulic fluids, and thermal cycling—requires further attention. Long-term joint performance depends on adhesive interphase chemistry. Silane coupling agents (e.g., GPTMS, APTES) and thiol-based compounds form covalent bonds with activated surfaces, enhancing hydrolytic and environmental resistance. Modern adhesives often incorporate functionalised nanomaterials (e.g., graphene oxide) and thermoplastic carriers to improve toughness and limit moisture and thermal mismatch. Surface treatments such as plasma and laser ablation increase surface energy and remove contaminants, while chemical functionalisation further strengthens the interphase, producing robust joints suitable for aerospace applications.

4. Innovative Materials and Hybrid Composites

Recent advancements in innovative materials and hybrid composites have significantly impacted aerospace applications, including landing gear design. Adhesive bonding, as highlighted in recent research [33] achieves optimal tensile and shear strength with a 0.5 mm adhesive layer, this finding is specific to the study, enabling effective load transfer under extreme cyclic stresses. Another study [34] on brittle epoxies suggests optimal bondline thickness of 0.2 mm. These studies indicate optimal thickness varies with adhesive type and application. However, environmental factors such as humidity and exposure to hydraulic fluids can weaken bond strength, necessitating adhesives with enhanced environmental resilience. To address these challenges, finite element analysis (FEA) is increasingly employed to predict joint performance under varying service conditions. Fracture mechanics models such as Cohesive Zone Modelling (CZM) and the Virtual Crack Closure Technique (VCCT) are invaluable tools for refining adhesive layer design. According to Tserpes et al. [35], VCCT excels at simulating sudden debonding, particularly under fatigue loading, by tracking energy-release rates and crack progression, though it requires embedding cohesive layers and is computationally more intensive. Conversely, CZM offers more efficient modelling—without the need for cohesive elements—and captures both crack initiation and propagation via traction–separation laws, making it particularly useful for mixed-mode and gradual failure scenarios. Hybrid methods combining VCCT and CZM have also emerged, delivering enhanced accuracy by leveraging the strengths of both approaches. This enables better design for durability and maintenance reduction, reinforcing adhesive bonding as a lightweight and reliable solution for landing gear systems.

In addition to these considerations, failure modes such cohesive, interfacial, and substrate failures are critical to certifiability and structural safety. These modes are influenced by surface treatments (e.g., sandblasting, plasma treatment), adhesive thickness, and environmental exposure. Recent experimental investigations [36] show that plasma-treated GFRP joints exhibit improved adhesion and reduced fibre-tearing, while novel adhesive systems such as carbon fibre veil interleaved epoxies, thermally expandable particle (TEP) modified adhesives, and iron oxide (Fe_3O_4) functionalized epoxies enhance debonding efficiency. These systems facilitate stress concentration, improve thermal conductivity, and enable induction heating, contributing to damage-free separation and improved certifiability of bonded structures.

Thermoplastic composites offer key advantages such as reduced handling and processing costs, requiring up to ten times less energy than thermoset composites and achieving cycle times measured in minutes rather than hours [3]. These materials generate less waste, as they are recyclable, unlike thermosets. Thermoplastic resins, such as Elium®, an acrylic resin and anionically polymerised polyamide 6 (APA-6), are gaining significant attention from both academia and industry due to their aforementioned advantages as well as their self-healing capabilities, and weldability [37–39]. Notable applications of these materials include the use of a PEEK matrix for the Boeing V-22 aircraft's nose gear door and the Northrop T-38 aircraft's main gear door, as well as a PPS matrix for the Fokker 50 aircraft's main landing gear fin and stringer [5]. Thermoplastic veils/meshes are used for both toughening the laminate [40] and adhesive bondline [41] by hybridisation.

CIDETEC's aerospace-grade 3R epoxy vitrimer resins combine thermoset properties with thermoplastic benefits such as thermoformability, welding, and reprocessing [42]. These resins enable cost-effective manufacturing, efficient repair (restoring up to 90% of original properties), and enhanced recyclability through mechanical remoulding or chemical dissolution.

Noobed Fabrics by Fureho [43] are non-crimp 3D textiles designed for enhanced performance and precise shape conformity. These fabrics incorporate fibres in both in-plane directions (X, Y, and $\pm\ \theta$ angles) and through the thickness of the material (Z direction), establishing three-dimensional reinforcement structures. The Z-direction fibres notably improve interlaminar shear strength and resistance to delamination [44].

Hybrid composites combine different fibres, matrices, or fabrics to optimise mechanical performance under tension, compression, and impact. GLARE, for example, integrates metal sheets and composites to achieve strength, durability, and low weight [45]. Carbon-boron fibre hybrids arrest translaminar fractures through longitudinal splitting, enhancing damage tolerance but at high cost [46]. Hybrid fabrics using carbon, glass, boron, and p-aramid fibres show tensile strengths of 377–455 MPa (warp) and 194–419 MPa (weft), with CF/BF composites offering superior impact resistance [47]. In fibre orientation hybridisation, WUW (woven-unidirectional-woven) laminates demonstrated the highest impact resistance and damage tolerance [48]. Thin plies (<100 μm) enhance damage suppression and pseudo-ductility, as illustrated in Figure 3, by promoting stable cracking and controlled delamination [49–51]. They improve strain margins and early failure detection, key for aerospace applications. Intrayarn hybrids provide high strength and stiffness but are more susceptible to manufacturing defects [52].

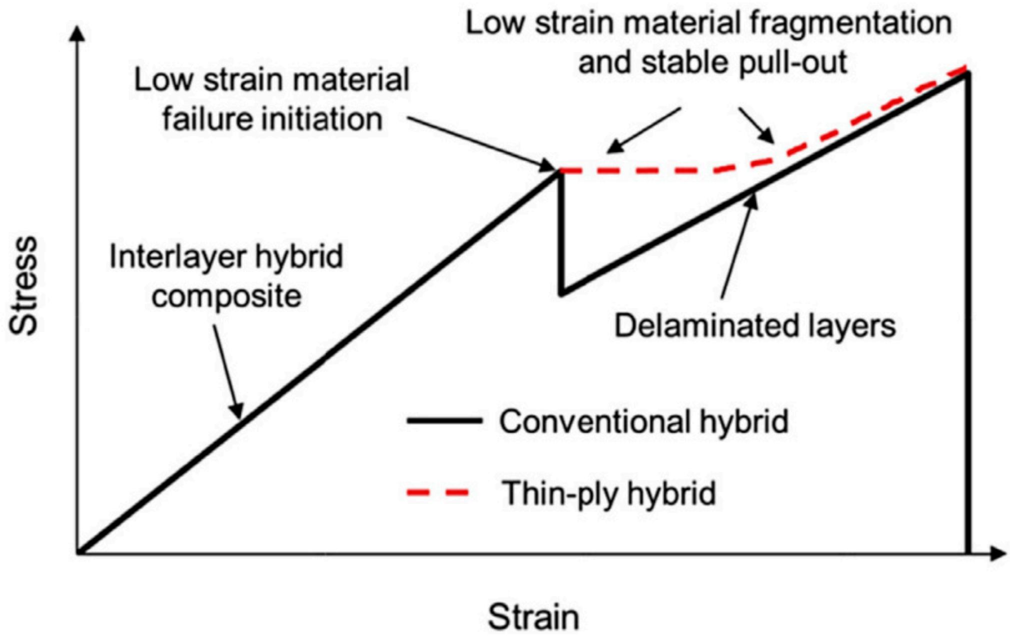
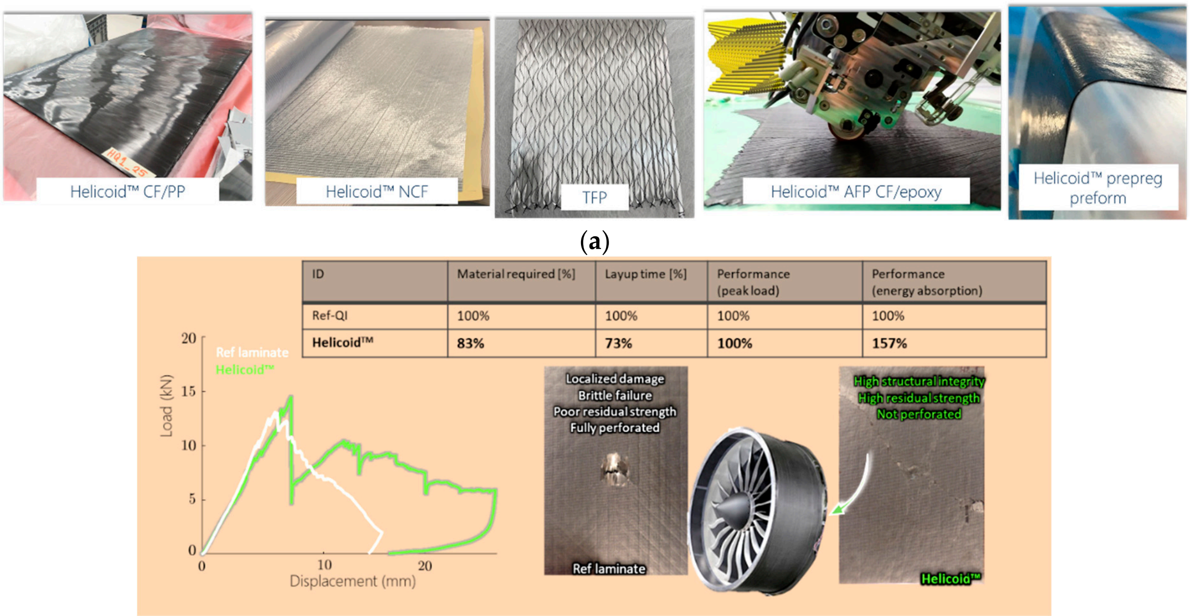


Figure 3. A schematic representation of the stress–strain response for conventional and thin-ply interlayer hybrid composites (i.e., all-carbon laminate) illustrates distinct behavioural differences [51].

Conventional aerospace laminates typically use plies oriented at 0°, 45°, −45°, and 90° to balance strength and flexibility. Double-Double (DD) laminates, with their $[\pm\varphi, \pm\psi]_n$ architecture, offer an innovative alternative by streamlining manufacturing and enabling efficient optimisation, as it is no longer constrained by mid-plane symmetry requirements, the ten percent rule, ply-blocking limits on ply nesting, and other design restrictions [53]. However, as DD laminates are proposed as non-symmetric coupling may occur and must be considered in structural applications where such effects are undesirable. These laminates provide significant advantages, including theoretical possible weight savings of over 45% [54]. Their even ply drops ensure smoother material transitions and reduced stress concentrations [53,55].

Bio-inspired manufacturing techniques, as developed by Helicoid Industries, further enhance composite performance by mimicking natural material arrangements (Figure 4a). Their technology has shown significant improvements, including a 74% reduction in catastrophic failure risk, 50% less dent depth under low-velocity impact, over 40% increased impact strength, a 20% boost in residual compression strength with reduced notch sensitivity, and over 100% increased energy dissipation, improving damage diffusion both in-plane and through-thickness (Figure 4b) [56]. Bio-inspired composites with randomised fibre networks offer tunable mechanical properties and energy absorption, and their translation into aerostructures could enable lightweight, durable, and sustainable aircraft designs [57].



(**b**)

Figure 4. (**a**) Helicoid™ preforms with different manufacturing methods, including dry fibre placement (Courtesy of Helicoid Industries Inc.). (**b**) Load–deflection curves from quasi-static indentation tests on Helicoid™ and conventional layups using aerospace-grade CFRP (200 gsm) manufactured via AFP. Insets show damage at the end of testing, highlighting the pierce-through resistance and retained structural integrity of Helicoid™ laminates [56,58].

Hybrid composites are also created in emerging technologies like FiberJoints [59,60] and Multi-Matrix Continuously Reinforced Composites (MMCRC) [61]. FiberJoints utilise patch-type inserts that redistribute force, enhancing the static and fatigue resistance of composite laminates. MMCRC combines thermoset polymer and metal matrices with fibre-bridged interfaces, resulting in improved strain redistribution, load sharing, and structural performance.

Despite their potential, and Staggered Enhanced Double-Double (SEDD) [62] designs require homogenisation to prevent warpage and depend on automated tape or ply placement (ATP/AFP) for precise ply angles, making them unsuitable for manual layup or RTM. Helicoid laminates necessitate robotic ply placement to maintain their architecture, typically with non-crimp fabrics (NCFs), and demand careful control to ensure consistent performance. Hybrid laminates such combination of low- and high-strain fibres can generate residual stresses due to mismatched coefficients of thermal expansion (CTEs) and complicate recycling and repair because of mixed fibre types.

The FAUSST local insert patch enables arc stud welding in composite structures using a hybrid glass-steel fibre design [63]. At just 1.5 mm thick, it integrates into laminates as thin as 2 mm, securely attaching fasteners while minimising structural impact. Compatible with methods like hand layup and RTM, it enhances load transfer and prevents galvanic corrosion, ensuring durability. By integrating these technologies, composite materials continue to evolve, meeting the growing demands for lightweight, durable, and efficient solutions in modern aerospace engineering.

AI and structural health monitoring (SHM) offer transformative solutions for composite aircraft landing gear systems, especially for the transition of landing gear design philosophy from safe life to damage tolerance [64]. Advanced signal processing methods such as Fast Fourier Transform (FFT), wavelet transforms (WT), empirical mode decomposition (EMD) and Hilbert–Huang transform (HHT) enable robust interpretation of sensor data, allowing detection of transient events and subtle damage signatures in noisy, non-stationary environments [65]. Building on these, AI models, including convolutional neural networks (CNNs), long short-term memory (LSTM)-based models, and support vector machines (SVMs) further optimise feature extraction, optimise load prediction and damage detection, enhancing real-time monitoring and predictive maintenance [65,66]. Hybrid approaches such as combining WT with CNNs have shown enhanced robustness for detecting delamination and impact damage in composites. In practice, SHM complements AI with Fibre Bragg Grating (FBG) and piezoelectric sensors to detect micro-damages, strain, and temperature changes, enabling condition-based maintenance, reducing downtime and extending component lifespan [67].

Integrating SHM with self-healing composites could further enhance resilience, enabling real-time damage detection and autonomous repair. Self-healing materials, employing mechanisms like microcapsules, hollow fibres, and graphene-enhanced vascular networks, improve structural reliability while reducing maintenance demands [68,69]. Innovations such as shape memory polymers and embedded heating systems enable impact resistance, thermal triggered repairs, and eco-friendly de-icing, supporting sustainability and operational efficiency in challenging environments [70]. Together, these technologies have the potential to enhance safety, durability, and cost-effective performance in future aerospace applications.

Certification of adhesive bonding in composite aircraft structures is governed by FAR/CS-25.603, 25.605, 25.613 and 25.571 [71], which require approved materials, validated processes and demonstration of durability and damage tolerance. AMC 20–29 "Composite Aircraft Structure" [72] provides the principal guidance, emphasising process control, prevention of weak bonds and a building-block approach to substantiation. Given the limited detectability of kissing bonds, current research in process monitoring and AI-based quality assurance directly supports these regulatory expectations by enhancing process reliability and providing quantifiable evidence for compliance.

5. Manufacturing Processes and Scalability

Autoclaving is widely employed in the aerospace and motorsport industries. It is the preferred method for curing thermosetting polymers and thermoset matrix composites, which are essential for creating robust and resilient aircraft parts. It is particularly effective for prepregs and resin-infused materials. This technique enhances the strength, durability, and performance of composite materials, enabling them to withstand the demanding conditions of aerospace applications [73]. An innovative patent [74] details a composite landing gear made with three-dimensional weaving. The landing gear consists of a central strut shaft (1), a wheel rocker arm (2), and a hydraulic damper (3). Both the central strut shaft (1) and the wheel rocker arm (3) are made from three-dimensionally braided carbon fibre components, as shown in Figure 5. The weaving scheme for the pillar central shaft (1) and wheel rocker arm (3) is structured as follows: the central shaft main body (5) of the pillar central shaft (1) utilises a three-dimensional six-way weaving technique, allowing for cross-sectional diameter variations by adjusting the number of yarns in specific sections. The pillar central shaft (1) has a total length of 45 cm, with three variable cross-sectional diameters of 14 cm, 12 cm, and 10 cm, respectively. Constructed from 3D braided carbon fibre (T300 and T700) with a fibre volume content of 45–65%, this lightweight, compact design offers exceptional resistance to compression, bending, and torsion, making it ideal for uneven runways. This three-point structural layout enhances the strength, impact resistance, and weight efficiency of the composite landing gear.

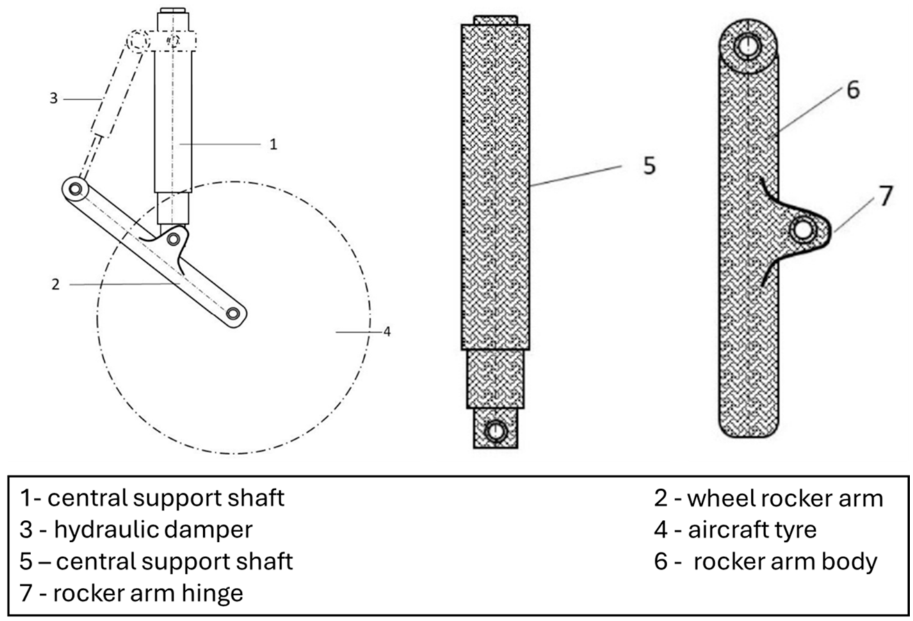


Figure 5. Three-dimensional weaved composite part [74].

An alternative to autoclave manufacture of carbon fibre composites is resin transfer moulding (RTM). RTM is widely adopted in the aerospace industry for its ability to produce complex, high-quality components with excellent dimensional accuracy such as CFRP ribs, stringers, radomes and fuselages [75–77]. Safran developed composite landing gear braces using Hexcel IM-7 fabric and RTM technology [78]. Cranfield University contributed to this process by employing tufting stitching for preform creation (Figure 6) [79], resulting in the first-ever composite landing gear brace designed with two leg struts to support the landing gear during touchdown [80], showcasing the potential of this pioneering technology.

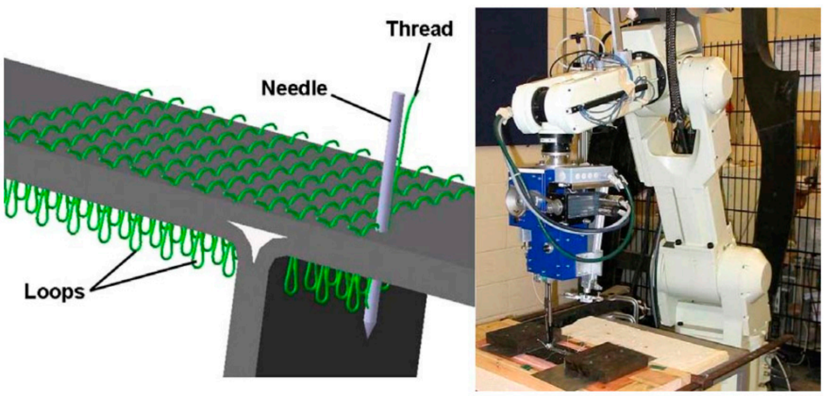


Figure 6. Schematic of tufting (**left**) alongside a six-axis Kawasaki robot arm fitted with a KSL KL150 tufting head operating at Cranfield (**right**) [79].

Filament Winding (FW) has long been employed to manufacture axisymmetric FRP components, including pipes, pressure vessels, pipe fittings, and drive shafts. Recent advancements in robotics have expanded FW's capabilities to produce components with more complex shapes such as a helicopter "fork," a structural component connecting the blade to the rotor, which is not axisymmetric [81].

A hybrid manufacturing approach combining FilaWin® (an advanced filament winding process) and RTM technology was used to develop a lightweight fibre-reinforced composite strut (I-Rod) for aircraft landing gear [82,83]. Static tensile and compression tests revealed the I-Rod's potential to replace heavier aluminium components, achieving weight savings of up to 50%.

While Automated Fibre Placement (AFP) is a well-established technology for thermoset prepregs, this technology has significantly improved the fabrication of fibre-reinforced thermoplastic (FRTP) composite components by enhancing fibre direction accuracy and reducing material waste compared to conventional methods such as hand layup. Modern AFP machines achieve fibre placement speeds of up to 3 m/s, and for large components, multiple tapes can be placed simultaneously to boost productivity [81]. This development is significant due to the unique advantages offered by thermoplastic composites, such as improved recyclability and the potential for out-of-autoclave processing.

Composite performance is highly sensitive to manufacturing quality. In RTM, porosity from incomplete impregnation or trapped air reduces interlaminar shear strength (ILSS) and accelerates fatigue-driven delamination; in joints, voids diminish bond area and toughness [84]. Autoclave processing achieves high fibre fractions and low porosity, but defects such as voids, wrinkles and residual stresses still lower ILSS, shorten fatigue life, and degrade joint durability through microcracking or poor adhesive contact [85]. Automated layup (ATL/AFP) introduces characteristic defects such as gaps, overlaps, fibre waviness and poor consolidation. These create resin-rich zones and weak interfaces that reduce ILSS and provide sites for delamination under cyclic loads [86]. In thermoplastic manufacturing, insufficient compaction or crystallinity further compromises interlaminar properties and joint quality. Overall, even minor defects critically influence shear strength, fatigue life and joint reliability, underscoring the need for rigorous defect control.

6. Conclusions and Future Outlook

This review highlights the potential role of polymer composites and adhesives in advancing aircraft landing gear systems while addressing sustainability and performance challenges. Replacing traditional metallic materials and mechanical fasteners with advanced composites and adhesives enables significant weight reductions, improving fuel efficiency and reducing emissions. These innovations align with the aviation sector's goals of achieving net-zero carbon emissions and enhancing operational sustainability.

Polymer composites, including bio-based and hybrid variations, offer high mechanical strength, corrosion resistance, and shock absorption, enhancing durability and cost-efficiency. Manufacturing techniques such as resin transfer moulding (RTM), compression moulding, and automated fibre placement (AFP), alongside emerging processes like overmoulding and 3D weaving, enable scalable production for aerospace applications.

Adhesive bonding provides lightweight, durable alternatives to mechanical fasteners. Advances in thermosets, thermoplastics, and vitrimers improve performance under cyclic stresses while supporting repairability and recyclability.

Hybrid composites, thin-ply laminates, and self-healing materials offer improved damage tolerance, safety, and operational efficiency. Bio-inspired designs, such as helicoid structures and pseudo-ductility mechanisms, reduce failure risks, while SHM systems and self-healing materials enable real-time damage detection and autonomous repair, minimising maintenance.

In conclusion, the continued innovation in polymer composites and adhesive technologies holds immense promise for the future of aircraft landing gear systems. These advancements not only address the critical need for weight reduction and improved performance but also align with the growing emphasis on sustainability within the aerospace industry. By addressing current challenges, such as recycling limitations, certification hurdles, cost constraints, and material compatibility, while fully embracing the potential of these materials, the aerospace sector can pave the way for safer, more efficient, and environmentally responsible air travel.

Funding: This research was funded by Airbus Operations Limited, and the reference number for the funding is CU01921121.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflict of interest.

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A review of polymer composites and adhesives for aircraft landing gear applications

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2025-09-02

Caglar H, Ayre D, Mills A, et al., (2025) A review of polymer composites and adhesives for aircraft landing gear applications. Aerospace, Volume 12, Issue 9, September 2025, Article number 794

https://doi.org/10.3390/aerospace12090794