The Evolution and Future of Composite Construction in Light Aircraft

Author: William Wu

Contents

Abstract

Within this study the historical development, current applications and future topics of light aircraft construction shall be analyzed. It describes the evolution of used materials and construction methods starting from traditional materials such as wood and aluminum to advanced composite materials. Furthermore, the different types of composite materials and construction methods are categorized, their advantages and disadvantages are discussed. The implementation in current aircraft models by leading manufacturers such as Diamond Aircraft, Cirrus, and Elixir is presented. Further, the challenges that likely arise with the adoption of advanced composites in general aviation are discussed and finally emerging trends and technologies that may be adapted in future aircraft construction are described.

1 Introduction

Over the past hundred and twenty years, after the first powered flights took place, the aviation industry went through significant transformations in the type of materials that are used and the applied construction techniques. From wooden biplanes to the modern airplanes made of advanced composite materials, the evolution of aircraft construction has been mainly the result of strive for improved performance, higher efficiency and enhanced safety. This study aims to provide a comprehensive overview of the historical development, current applications, and future directions of composite construction in light aircraft.

2 Historical Development of Materials in Light Aircraft

The first motorized aircraft, such as the Wright Flyer, were constructed mainly from wood and fabric since the material was available, had sufficiently lightweight properties, and the airplane could be fabrication with those materials [1].

When the aviation technology advanced, aluminum became the commonly used material. Designs using an aluminum structure offered better strength-to-weight ratios and manufacturability [2]. After World War II the adoption of aluminum in general aviation aircraft designs was common practice. Examples of such are aircraft are the popular Cessna 172 and Piper PA-28. These also feature semi monocoque design for efficient load distribution [3]. However, there are limitations of metal structures, which include mainly the susceptibility to fatigue and corrosion. That lead to the exploration of alternative materials [4][5].

Images 1: Wright Flyer [6], Cessna C172 [7], Piper PA-28 [8] (left to right)

The introduction of composite materials in the late 1950s and late 1960s started a significant change in the way small airplanes are constructed. Composites, such as fiberglass and carbon fiber reinforced polymers (GFRPs and CFRPs), offered even better strength-to-weight ratios and greater design flexibility compared to aluminum designs. Pioneering sailplanes and aircraft like the fs24 Phönix, the Windecker Eagle and the SB 10 demonstrated the potential of composites, and paved the way to ever growing integration into certified aircraft designs.

The first aircraft using composite construction was the glider fs24 Phönix. It was built entirely from glass-fiber reinforced plastic (GFRP) using sandwich construction with balsa wood as the core material. The first flight took place on November 27th, 1957. The fs24 Phönix played a leading role in the development of modern glider construction. Akaflieg Stuttgart developed this glider, and Bölkow later produced it in series [9].

The first composite aircraft that was certified by the Federal Aviation Administration (FAA) was the Windecker Eagle. The first flight took place in 1969 and it was awarded with a type certificate under Part 23 two years later. This has been achieved following several years of development of Dr. Leo Windecker and Dr. Fairfax Windecker together with Dow Chemical Company. They jointly aimed to develop a lightweight fiberglass reinforced plastic structure specific for aviation use. Only a limited number of airplanes was finally produced, yet this achievement marks a significant milestone in the field of composite materials [10].

The SB 10 sailplane, which was designed and built by Akaflieg Braunschweig is a high-performance two-seat glider. The first flight took place on July 22nd, 1972. The glider has a maximum wingspan of 29 meters, which makes it the largest none motorpowered glider in the world. It was also the first civilian aircraft that incorporated carbon fiber reinforced plastic (CFRP) in primary structural components. It is noteworthy, that in the winter of 1979/80, the SB 10 was brought to and flown in Australia, where, in collaboration with renowned pilot Hans-Werner Grosse, four world records for two-seater gliders were set [11].

Images 2: fs24 [12], Eagle [13], SB10 [14] (left to right)

The application of composites in small aircraft can also be seen as the cradle for composite designs in large airplanes. In 1970s designs it started from very little weight share of composite material of the total structural weight. Since then the share of composite material was continuously growing in new designs as it can be seen in Figure 1.

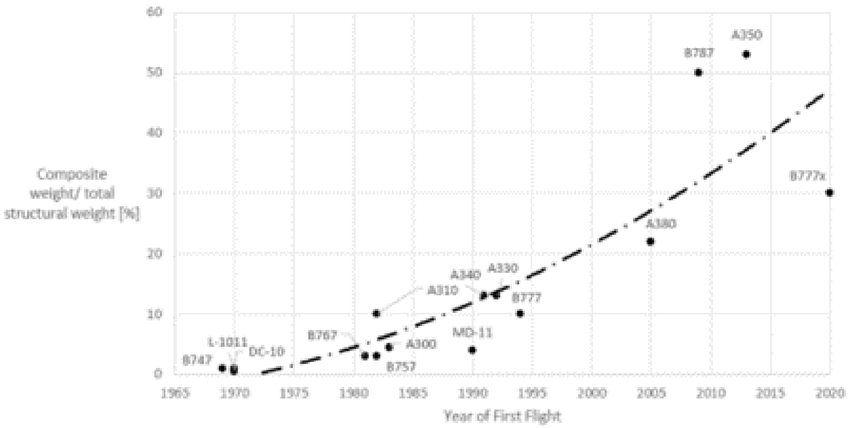

Figure 1: Share of composite material used in wide-body aircraft, 1965 – 2020. [15]

3 Properties and Classification of Composite Materials

Per definition, composite materials are designed by combining two or more constituent materials with distinct physical or chemical properties. The resulting material shows characteristics superior to those of each individual components [16].

In general, composite materials may be distinguished by the used matrix material and the used reinforcements. As such, they may be classified into three different types of composites per matrix material, which are Ceramic Matrix Composites (CMCs), Polymer Matrix Composites (PMCs), and Metal Matrix Composites (MMCs). These can further be structured by the type of reinforcement and particularly PMCs by the matrix hardening system as shown in Figure 2 [16].

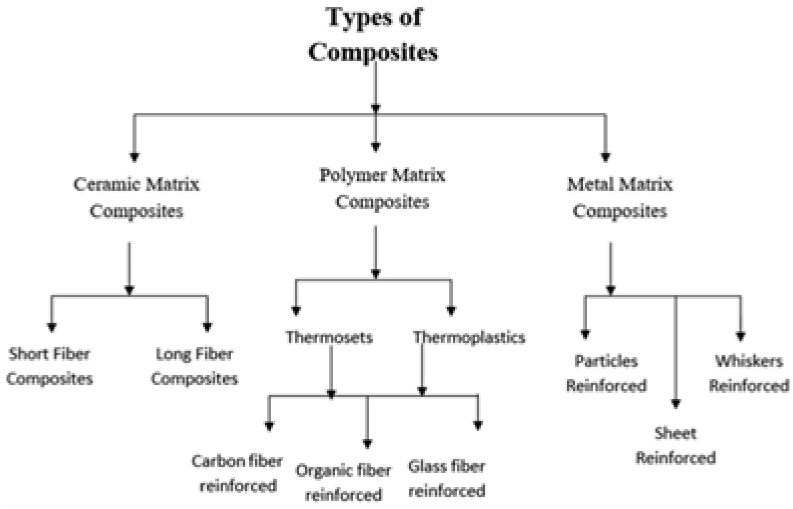

Figure 2: Types of Composites [16]

The different types of composites can be described as follows:

- Ceramic Matrix Composites (CMCs): CMCs consist of a ceramic matrix reinforced with fibers or particulates to improve toughness and thermal resistance. A typical application of CMCs is in high-temperature environments such as turbine engines [16].

- Polymer Matrix Composites (PMCs): PMCs use a polymer resin matrix (thermoset or thermoplastic) which is reinforced with fibers such as carbon, glass, or aramid. The fibre-reinforcements provide the high tensile strength and stiffness, whereas the polymer matrix enables the load transfer and protects the fibres form the environment. PMCs typically provide excellent strength-to-weight ratios and corrosion resistance [16].

- Metal Matrix Composites (MMCs): Metal Matrix Composites (MMCs): MMCs consist of a metallic matrix such as aluminum, magnesium or titanium and are reinforced with ceramic or metallic phases. They can be further classified into laminate, fiber-reinforced, and particle-reinforced composites. Each of those are normally optimized for specific applications. MMCs usually provide superior mechanical properties, wear resistance, and thermal stability. This makes them typically very suitable aerospace and automotive applications. [16].

As described above, due to their typically outstanding mechanical properties, such as the excellent strength-to-weight ratio, corrosion resistance and their relatively easy processability, PMCs are the most used composite materials in aviation. PMCs are often used for construction of structural components in aircraft fuselages, wings, and interior panels. They normally offer significant weight savings compared to metal which leads to improved fuel efficiency and higher performance. Advanced manufacturing techniques, such as automated fiber placement and resin transfer molding, may further enhance the quality and usability of PMCs for modern aerospace applications [16].

PMCs are known to have generic advantages and disadvantages which are described in Table 1:

Advantages of PMCs are:	Disadvantages of PMCs are
• High Strength-to-Weight Ratio: This allows for the design of lower weight components compared to traditional metal parts while retaining the required strength. [16] • Corrosion Resistance: PMC parts remain corrosion resistant also in harsh environments, whereas metal typically are not. This helps reducing maintenance costs and longevity of components. • Design Flexibility: Parts can be shaped to complex forms which will then be aerodynamically or structurally optimized[16] • Fatigue Resistance: PMCs generally exhibit good fatigue performance under cyclic loading. This allows also prolong structural life of critical components. [16] • Tailorable Properties: Fiber orientation and matrix selection allow customization of stiffness, strength, and thermal properties. This may further support lightweight designs. [16]	• Temperature Limitations: Thermoset PMCs will degrade at high temperatures, which is limiting their potential use in components exhibit to extreme environments. [16] • Moisture Absorption: Some polymer matrices absorb moisture. This can affect their dimensional stability and negatively effect mechanical properties. This limits their potential use in certain environments. [16] • Difficult Repairability: Damage detection and repairs of PMC components are typically more complex compared to metals components due to potential internal damages. [16] • High Manufacturing Costs: Need for auxiliary material and necessary processes like autoclave curing and prepreg handling increase production costs. [16] • Recycling Challenges: PMCs are difficult to recycle due to the cross-linked nature of thermoset matrices. The separation of the matrix from the reinforcement may not be possible. [16]

Table 1: PMCs’ generic advantages and disadvantages

Composite construction methods can be broadly classified into the following categories (Figure 3):

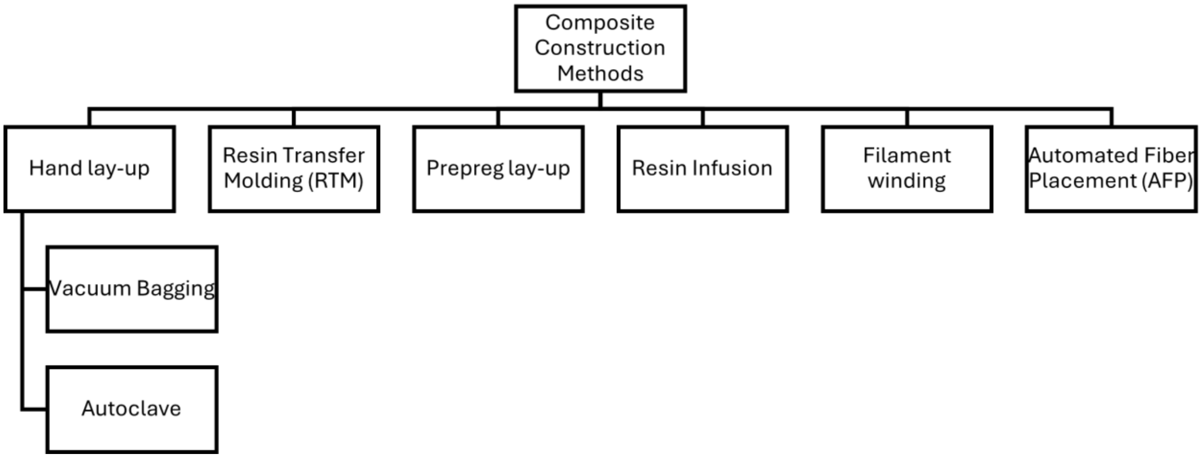

Figure 3: overview of composite construction methods (self, compare [17])

Those construction methods of composite materials can be described as follows [17]:

- Hand lay-up: Is the manual placement of fiber layers impregnated with resin. It can be combined
    - with Vacuum Bagging for high fiber volume fractions and low porosity
    - with Autoclave curing techniques for even higher fiber volume fractions and lower porosity
- Resin Transfer Molding (RTM): Resin is injected into a closed mold containing dry fibers.
- Prepreg lay-up: Pre-impregnated fibers are laid into molds and cured under heat and pressure.
- Resin Infusion: Resin is drawn through dry fiber layers using vacuum pressure, resulting in improved fiber wetting and reduced void content.
- Filament winding: Continuous fibers are wound under tension over a rotating mandrel.
- Automated Fiber Placement (AFP): Robotic placement of fiber tows with precise control

Each method offers distinct advantages and limitations, as summarized in the table below (Table 2):

Method	Advantages	Disadvantages
Hand lay-up	Low cost, simple tools, suitable for small production [17]	Labor-intensive, inconsistent quality [17]
Resin Transfer Molding (RTM)	Good surface finish, better quality control [17]	Higher tooling cost, complex setup [17]
Prepreg lay-up	High strength, consistent properties [17]	Requires refrigeration, expensive [17]
Resin Infusion	Improved fiber wet-out, scalable for medium production [17]	Requires vacuum setup, sensitive to process parameters [17]
Filament winding	Efficient for cylindrical shapes, high fiber content [17]	Limited to simple geometries [17]
Automated Fiber Placement (AFP)	High precision, suitable for complex shapes [17]	High capital investment [17]

Table 2: Summary of advantages and limitations of composite construction methods

4 Current Applications of Composite Materials in Light Aircraft

As described above, advanced composite materials are assessed to have become more and more prevalent in the construction of aircraft. The significant advantage of the materials in terms of weight reduction, aerodynamic efficiency and corrosion resistance make them the material of choice for several leading manufacturers in general aviation. In this chapter an exemplary overview of three renowned general aviation aircraft manufacturers (Diamond Aircraft, Cirrus and Elixir) that have adopted composite technologies in their production models is provided.

Diamond Aircraft is a globally operating manufacturer. It is recognized for its all-composite aircraft. All their models, namely the HK36, DV20, DA20, DA40, DA50 and DA62 feature airframes constructed almost entirely from glass- and carbon-fiber reinforced polymers. This material selection is the basis of the aircraft's lightweight structure and fuel efficiency and is providing high strength and extraordinary durability. Diamond Aircraft uses several manufacturing methods, but mainly semi-automated hand lay-up combined with vacuum bagging and autoclave curing techniques and vacuum infusion are in use[18].

Cirrus Aircraft, based in the United States, uses composite construction in its SR aircraft series, such as SR20 and SR22 and the Vision Jet aircraft. These aircraft use carbon fiber and fiberglass composites for the fuselage and wings to enhance performance and safety. Cirrus applies advanced manufacturing methods such as pre-preg construction and resin transfer molding (RTM) and does intensive quality control to meet certification standards [19].

Elixir Aircraft, a younger company from France, has introduced innovative composite technologies in its Elixir model. The aircraft is built using a single-piece carbon fiber monocoque structure to reduce the number of parts and potential failure points. This technique simplifies manufacturing and maintenance while improving overall safety and performance. Elixir's use of thermoplastic composites and automated production processes shows the trend toward more efficient and scalable composite manufacturing in general aviation [20].

These examples illustrate several different applications of composite materials in light aircraft design and construction. They also show the trend that the industry is moving towards more advanced composite materials and manufacturing techniques in order to enhance performance, safety of the products and sustainability.

5 Challenges in the Use of Composite Materials

As elaborated in Chapter 3, composite materials have numerous advantages when used in light aircraft construction. Yet, there are several challenges known to limit the widespread adoption of these material. These challenges do reach from economic, technical, regulatory to environmental aspects.

Cost is typically identified as one of the primary challenges. Advance composite materials in general, but especially advanced carbon fiber reinforced polymers (CFRPs), are significantly more expensive than traditional materials like aluminum. This high cost typically comes not only from the raw materials alone, it comes also from the specialized manufacturing processes and the highly skilled and trained workforce that is required to manufacture components. Thus, this cost structure can be a barrier for smaller aircraft manufacturers who typically operate with budget constraints [21].

Certification of composite structures in aircraft requires additional and specific effort. Regulatory authorities such as the Federal Aviation Administration (FAA), European Union Aviation Safety Agency (EASA) and many others have established specific requirements and regulations for certification of composite structures. These rules require extensive testing and documentation to certify composite airframes. The variability in composite material properties, which may be widely influenced by factors such as fiber orientation, resin content, and workshop conditions, has to be considered in the certification process. Overall, this may lead to longer development timelines and increased costs for manufacturers [22].

The complexity of manufacturing composite structures may also be a limiting factor. Processes such as hand lay-up, resin transfer molding (RTM), and autoclave curing typically require very precise control of temperature, pressure and humidity. In addition, they are known to be highly sensitive to environmental conditions and operator skill [23][24]. It is required to introduce stringent process and manufacturing environment control requirements, which in turn demand significant investment in infrastructure, specialized tooling and a close quality control system. Additionally, the learning curve for technicians and engineers transitioning from metal to composite fabrication can be steep, This requires comprehensive training and certifications tailored to composite technologies in use [25][26].

Maintenance and structural repair may present an additional layer of complexity. While metallic airframes can typically be restored using conventional mechanical processes like riveting or welding, the maintenance and repair of composite structures require specialized procedures. One critical concern is that damage within a composite laminate is not always directly detectable on the surface. Such potentially hidden damages need the application of advanced non-destructive testing (NDT) methodologies to assess structural integrity. Examples are ultrasonic inspection or thermography [27][28]. These methods require specialized equipment together with trained and certificated personnel, which increases maintenance complexity and cost. Composite repairs typically require strict environmental controls and certified facilities to ensure structural integrity of the repaired structure [27].

Finally, the environmental impact of composite materials is becoming a growing concern. Although the material may provide weight savings to the aircraft which can reduce fuel consumption and emissions during operation, their production and end-of-life disposal have environmental challenges. The manufacturing of carbon fiber requires significant energy input [29]. Moreover, recycling composite materials seems presently a complex and underdeveloped field. While metals can be melted and reused, composites impose a difficulty of separating the reinforcements from the matrix. This in combination with the lack of mature recycling technologies currently they often end up in landfills [30]. With the further increasing share of composites in aircraft structures this likely presents a major challenge for future recycling efforts [15].

Addressing these challenges is deemed essential for the continued advancement and adoption of composite materials in general aviation. Innovations in those areas are suggested to be the focus for the industry.

6 Future Trends and Technologies

The demand for higher performance of materials, parts and processes, sustainability, and cost-efficiency is seen driving significant advancements in the field of composite construction in light aircraft. As the aviation industry continues to grow, several emerging trends and technologies are believed to shape the future of composite materials and their manufacturing processes.

The use of thermoplastic composites in aircraft is seen as one of the most promising developments. These materials may offer advantages such as improved impact resistance, recyclability and reduced processing times compared to traditional thermoset composites [31][32]. Thermoplastics can be reheated and reshaped, that would allow for easier repairs and end-of-life recycling, which aligns with the focus on environmental sustainability in aerospace and other industries [33].

Automation in composite manufacturing is another prevailing desire. Automated Fiber Placement (AFP) and Automated Tape Laying (ATL) technologies are kown to increasingly being adopted to enhance precision, reduce labor costs and improve production rates [34][35]. These methods can further enable the creation of complex geometries with minimal material waste. This should be particularly beneficial for small aircraft manufacturers aiming to optimize structural efficiency and reduce production overhead [36].

Additive manufacturing such as 3D printing, is becoming more popular and practically available in aerospace applications. While traditionally used for prototyping only, advancements in materials and printing techniques now allow the production of structural composite components [37][38]. This technology can enable rapid iteration, customization and the integration of complex internal structures that would be difficult or impossible to achieve with conventional methods [39][40].

Sustainability remains a central concern in the development of future composite technologies. Researchers are exploring bio-based resins and natural fiber reinforcements, such as flax and hemp, to reduce the environmental footprint of composite production [41][42]. These materials may offer the potential for biodegradable or recyclable components, contributing to a circular economy in aviation manufacturing. For instance, recent efforts by institutions like NASA and Oak Ridge National Laboratory highlight the push toward recyclable composites and bio-inspired materials for aerospace applications [43][44].

Furthermore, the integration of composite structures with electric propulsion systems seem to be a key area of innovation. Electric aircraft may benefit from the lightweight nature of composites, which helps offset the weight of batteries and improves overall energy efficiency [45][46]. Manufacturers are proposing designs of airframes that seamlessly incorporate battery housings and electric motor mounts into the composite structure. This shall enhance performance and reduce assembly complexity. NASA’s X-57 Maxwell technology demonstrator and other experimental platforms already illustrate how composite wings and spars shall be optimized for electric propulsion, enabling aerodynamic efficiency and structural integration [47].

In conclusion, a convergence of material science, automation, and sustainability characterizes the future of composite construction in light aircraft. As these technologies mature, they are expected to significantly change and advance the design, manufacturing, and operational practices of general aviation. They will be paving the way for safer, greener, and more efficient aircraft.

7 Conclusion

The study describes the advantages of use of advanced composite materials in light aircraft. These include the excellent strength-to-weight ratios, corrosion resistance and design flexibility. It also shows the challenges in the application of advanced composite materials. The future of composite construction in light aircraft is clearly depending on the convergence between material science, advanced automation, and the solutions for sustainability. Innovations reaching from the development of thermoplastics and additive manufacturing to sophisticated automated fiber placement techniques and the push for sustainable materials are enabling the design of structures that are more efficient and environmentally responsible. These will set the stage for the next generation of general aviation aircraft made from composite.

Acknowledgements

I would like to thank Robert Kremnitzer for all the support throughout writing this paper.

References

[1] History.com Editors. (2025). Wright Brothers: First flight, plane & Kitty Hawk. HISTORY. https://www.history.com/articles/wright-brothers [www.history.com]

[2] LibreTexts. (2021). Materials in aircraft. Engineering LibreTexts. https://eng.libretexts.org/Bookshelves/Aerospace_Engineering/Fundamentals_of_Aerospace_Engineering_%28Arnedo%29/04%3A_Aircraft_structures/4.02%3A_Materials/4.2.02%3A_Materials_in_aircraft

[3] AOPA (2014) / Aircraft Owners and Pilots Association. (2014). How it works: Monocoque structure. AOPA Flight Training Magazine. https://www.aopa.org/news-and-media/all-news/2014/april/flight-training-magazine/how-it-works

[4] AOPA (n.d.)/Aircraft Owners and Pilots Association. (n.d.). Metal fatigue and corrosion. AOPA Safety; Spotlight: Aging Aircraft. https://www.aopa.org/training-and-safety/online-learning/safety-spotlights/aging-aircraft/metal-fatigue-and-corrosion

[5] FAA (2018) / Federal Aviation Administration. (2018). Corrosion control for aircraft (Advisory Circular AC 43-4A). https://www.faa.gov/documentlibrary/media/advisory_circular/ac_43-4a_.pdf

[6] Wright Flyer Image: Smithsonian Institution. (n.d.). Wright Flyer [Photograph]. National Air and Space Museum. Retrieved October 9, 2025, from https://ids.si.edu/ids/deliveryService?id=NASM-NASM2022-00100A-000001&max=900

[7] Cessna 172 Image: Wikipedia contributors. (n.d.). Cessna 172S Skyhawk SP [Photograph]. Wikipedia. Retrieved October 9, 2025, from https://upload.wikimedia.org/wikipedia/commons/a/ae/Cessna_172S_Skyhawk_SP%2C_Private_JP6817606.jpg

[8] Piper PA-28 Image: Wikipedia contributors. (n.d.). Piper PA-28-181 [Photograph]. Wikipedia. Retrieved October 9, 2025, from https://upload.wikimedia.org/wikipedia/commons/a/af/26-09-04_PH-BVT_Piper_PA-28-181.JPG

[9] Akaflieg Stuttgart. (n.d.). FS24 – Phönix. Akaflieg Stuttgart. Retrieved October 9, 2025, from https://akaflieg-stuttgart.de/en/projects/fs24-phoenix/

[10] National Air and Space Museum. (n.d.). Windecker Eagle I. Smithsonian Institution. Retrieved October 9, 2025, from https://airandspace.si.edu/collection-objects/windecker-eagle-i/nasm_A19850619000

[11] Akaflieg Braunschweig. (n.d.). SB 10. Retrieved October 9, 2025, from https://akaflieg-braunschweig.de/projekte/sb10/

[12] fs24 Phönix: Akaflieg Stuttgart. (n.d.). FS24 Phönix [Photograph]. Akaflieg Stuttgart. Retrieved October 9, 2025, from https://akaflieg-stuttgart.de/wp-content/uploads/2014/05/cropped-fs24-1.jpg

[13] Windecker Eagle: Smithsonian Institution. (n.d.). Windecker Eagle I [Photograph]. National Air and Space Museum. Retrieved October 9, 2025, from https://ids.si.edu/ids/deliveryService?id=NASM-A19850619000_AER02&max=900

[14] SB 10: Akaflieg Braunschweig. (n.d.). SB 10 [Photograph]. Akaflieg Braunschweig. Retrieved October 9, 2025, from https://akaflieg-braunschweig.de/wp-content/uploads/2019/08/JPEG_LPE7528_.jpg

[15] Scheelhaase, J., Müller, L., Ennen, D., & Grimme, W. (2022). Economic and environmental aspects of aircraft recycling. Transportation Research Procedia, 65, 3–12. https://doi.org/10.1016/j.trpro.2022.11.002

[16] Farahmand, B. (2025). Understanding of Composite Materials (Constituents of Composites). In Fundamentals of Composites and Their Methods of Fabrications (pp. 1–17). Springer. https://doi.org/10.1007/978-3-031-80201-0_1

[17] Campbell, F. C. (2004). Manufacturing Processes for Advanced Composites. Elsevier Ltd., ISBN 1856174158

[18] Diamond Aircraft Industries. (2023). *DA42 technical specifications*. Retrieved October 9, 2025, from https://www.diamondaircraft.com

[19] Cirrus Aircraft. (2023). *SR series overview*. Retrieved October 9, 2025, from https://www.cirrusaircraft.com

[20] Elixir Aircraft. (2023). *Elixir design philosophy*. Retrieved October 9, 2025, from https://elixir-aircraft.com

[21] Irving, P. E., & Soutis, C. (2019). Polymer Composites in the Aerospace Industry (2nd ed.). Woodhead Publishing. https://doi.org/10.1016/C2017-0-04194-8

[22] Federal Aviation Administration. (2021). *Aircraft materials and construction*. FAA-H-8083-30A.

[23] NASA. (n.d.). Preferred design and manufacturing guideline for aerospace composites (Guideline No. GD-ED-2205). https://extapps.ksc.nasa.gov/Reliability/Documents/Preferred_Practices/2205.pdf

[24] Cairns, D. S., & Shramstad, J. D. (2000). Evaluation of hand lay-up and resin transfer molding in composite wind turbine blade manufacturing (Technical Report No. 760737). U.S. Department of Energy. https://doi.org/10.2172/760737

[25] American Composites Manufacturers Association. (n.d.). Certified Composites Technician (CCT) program. https://acmanet.org/education/certified-composites-technician-program/

[26] Davis Technical College. (n.d.). Composite materials technology program orientation. https://www.davistech.edu/media/0khl2mps/comp-0000-composite-materials-technology- orientation.pdf

[27] Federal Aviation Administration. (2016). Repairs and alterations to composite and bonded aircraft structure (Advisory Circular AC 43-214A). https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_43-214A.pdf

[28] Alexander, R. (2000). Repairing composite surfaces. EAA Sport Aviation. Retrieved from https://www.eaa.org/eaa/aircraft-building/builderresources/while-youre-building/building-articles/composite/repairing-composite-surfaces

[29] U.S. Department of Energy. (2017). Potential energy saving opportunities in the manufacturing of lightweight materials: Carbon fiber reinforced polymer composites. https://www.energy.gov/sites/prod/files/2017/12/f46/Carbon_fiber_bandwidth_study_2017.pdf

[30] Royal Society of Chemistry. (n.d.). Chemistry-enabled sustainable composites. https://www.rsc.org/policy-and-campaigning/environmental-sustainability/sustainable-composite-materials

[31] Krueger, R., & Bergan, A. (2024). Advances in thermoplastic composites over three decades – A literature review (NASA TM–20240005376). NASA Langley Research Center. https://ntrs.nasa.gov/api/citations/20240005376/downloads/NASA-TM-20240005376.pdf

[32] Thomason, J. L., & Rudeiros-Fernández, J. L. (2018). A review of the impact performance of natural fiber thermoplastic composites. Frontiers in Materials, 5, Article 60.

[33] Krawczak, P., & Maffezzoli, A. (2020). Editorial: Advanced thermoplastic composites and manufacturing processes. Frontiers in Materials, 7, Article 166.

[34] Juarez, P. D., Cramer, K. E., & Seebo, J. P. (2016). Advances in in situ inspection of automated fiber placement systems (NASA Technical Report No. 20160009052). NASA Langley Research Center. https://ntrs.nasa.gov/api/citations/20160009052/downloads/20160009052.pdf

[35] Uzman, B. (2024). Automated Fiber Placement – A Panel Discussion: Modeling and Simulation. Coriolis Composites USA Inc. https://acmanet.org/wp-content/uploads/2024/02/TCC20-AFP-panel.pdf

[36] Grimshaw, M. N. (2001). Automated tape laying. In Composites (Vol. 21, pp. 480–485). ASM International.

[37] Singamneni, S., Lv, Y., Hewitt, A., Chalk, R., Thomas, W., & Jordison, D. (2019). Additive manufacturing for the aircraft industry: A review. Longdom. https://www.longdom.org/open-access/additive-manufacturing-for-the-aircraft-industry-a-review-18967.html

[38] NASA. (2024). Advances in thermoplastic composites over three decades – A literature review (NASA TM–20240005376). https://ntrs.nasa.gov/api/citations/20240005376/downloads/NASA-TM-20240005376.pdf

[39] MIT News. (2025, September 25). Technique makes complex 3D printed parts more reliable. https://news.mit.edu/2025/technique-makes-complex-3d-printed-parts-more-reliable-0925

[40] Ferguson, F. (2024). Maximizing additive manufacturing in aerospace and defense. Advanced Manufacturing. https://www.advancedmanufacturing.org/industries/maximizing-am-s-potential/article_4d8dc668-9c4f-11ef-a0b1-7f51ae4e180d.html

[41] Chang, B. P., Mohanty, A. K., & Misra, M. (2020). Studies on durability of sustainable biobased composites: A review. RSC Advances, 10(30), 17955–17999.

[42] Shahzad, A. (2011). Hemp fiber and its composites – a review. Journal of Composite Materials, 46(8), 973–986.

[43] Williams, T. S. (2023). Bio-inspired materials and processes for aerospace environments. NASA Glenn Research Center.

[44] Oak Ridge National Laboratory (ORNL). (2022, November 10). Recyclable composites help drive net- zero goal. https://www.ornl.gov/news/recyclable-composites-help-drive-net-zero-goal

[45] Lents, C. E. (2020). Hybrid electric propulsion: Architectural design space and potential benefits. Mechanical Engineering, 142(06), 54–55.

[46] Saha, A., & Ghassemi, M. (2025). Electrical system architecture for aviation electrification. arXiv. https://doi.org/10.48550/arXiv.2510.03887

[47] Moore, J. B., & Cutright, S. E. (2020). Structural analysis and performance-based validation of a composite wing spar for electric aircraft (NASA Technical Report No. 20200002440). NASA Langley Research Center.