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A Multiscale Review of Carbon and Aluminium Based Reinforced Composite Materials for Aero-Structural Wing Components in Light Aircraft Design

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Abstract: *The aerospace and aeronautical industries have shifted their focus from using traditional materials to using composite materials, mainly due to excellent strength to weight ratio and superior mechanical properties such as high strength. This paper focuses on the key finding of previous research work made by different researches on composite materials in aeronautical industry and draws a conclusion on the added benefits and directing the best composite material which could be used for manufacturing parts in aeronautical industry. The primary focus is on three parts namely aileron, wing spar and wing skin. When it comes to wing spar the observations were made on the amount of load a certain composite material can bear, there was also analysis done on the number of layers and which type of binding material and reinforced fiber is beneficial over other. Observations that were made about the wing skin were based on a newly developed material that was later put through further testing to determine its capabilities. This study suggests that, Graphite and Kevlar 49 Fiber combination is the most superior material due to its cost-effectiveness and fracture toughness. After a thorough comparison of four potential materials Fiber Metal Laminate composed of Glass Fiber Epoxy and 2023 T3 Aluminium, was determined as the most suitable for Aircraft Wing Skin. TR50 Carbon Fiber with R367-2 Epoxy matrix prove to be the most superior material for Wing Spar.*

Materials and Methods*: This study reviewed the use of composite materials in the design of aircraft wing structures, focusing on the aileron, wing spar, and wing skin of a light aircraft. Relevant literature was analyzed to identify optimal composite combinations based on parameters such as tensile strength, stiffness, weight, fatigue resistance, and cost-effectiveness. For the aileron, materials such as Graphite/Kevlar 49 hybrid, HTA 5131 fiber with RTM6 resin, and CF/PEI thermoplastics were evaluated. The wing skin analysis considered Fiber Metal Laminates (FMLs), Aluminium-Lithium alloys, and Boron/Epoxy composites, emphasizing wear resistance, fatigue life, and structural integrity. Wing spar materials were assessed based on mechanical performance under load, incorporating experimental data from carbon fiber/epoxy composites (e.g., TR50 carbon fiber with R367-2 epoxy), finite element modeling, and physical testing. Each section of the wing structure was evaluated using data from tensile, compression, fatigue, and impact tests reported in prior research. Comparative tables were developed to weigh the advantages and disadvantages of each composite system. The final selection of materials was based on overall performance, mechanical compatibility, and suitability for light aircraft application, with recommendations guided by documented test results and design optimization studies.*

Key Word*: Composite materials, Aircraft, Aileron, Wing spar, wing skin*

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I. Introduction

With the increase in the demand for the composite materials in every sector, aerospace and aeronautical industry have also shifted their focus from using traditional materials like steel, aluminium, titanium to using composite materials to manufacture parts of the passenger, military aircraft or rocket. We get a material of superior properties than other when two or more materials are combined, which are often a reinforcing fibre like carbon, glass, or aramid and a binding polymer matrix such as epoxy, polyester, or phenolic resin [1]. One of the main benefits of using composite materials is its high strength to weight ratio, as per studies composite materials are almost 50% lighter than traditional metals and other materials for the same amount of weight [2]. This weight reduction can offer multiple advantages like better fuel efficiency and increased payload capacity, which leads to increasing range of aircraft and hence reducing the operational cost of aircraft to the airlines [3]. Generally, the traditional metals have a tendency to corrode over time due to the effect of atmospheric air and other gases, but the composite materials have a great advantage of being corrosion and fatigue resistant, this leads to restriction of development of cracks and structural damages. For instance, a study tested the corrosion resistant of A304 SS when coated with PANI+TiO2 and found that coating of composite not only reduces corrosion but also restricts the crack to be developed [4]. As the structural damages are reduced, hence, the maintenance cost is also reduced. Furthermore, composite materials are also more flexible than metals making them absorb more energy in case of any impact making them less prone to catastrophic failure. Another advantage of composite materials is their better flexibility, the composite materials can be moulded into any shape of complex geometries, allowing the designer to develop more aerodynamic efficient design [5]. Moreover, composite materials offer great customization and optimization opportunities allowing the designer to tailor the part as per the need and as per the property's requirements.

Composite materials are used in numerous current aircraft designs, including the wings, tail, and fuselage of several modern passenger aircraft. Like for instance, a study was conducted to check the advantages of composite material over traditional aluminium, in which it was concluded that S-glass/epoxy had higher stiffness and greater weight reduction as compared to aluminium for an Airbus A320 [6]. Further the Boeing 787 Dreamliner's fuselage, skin, stringers and frame are made of nearly 50% composite materials [2]. The Airbus A350 XWB has its wings and fuselage made of almost 53% of composite materials, reducing the weight of aircraft considerably [7]. Additionally, the F-35 Lightning II fighter jet's horizontal tail is made more durable than its metal counterparts by using composite materials [8]. Hence, it has proven advantageous to use composite material in place of metal parts.

Due to the benefits mentioned, the aircraft manufacturers have now started using composite materials as it offers better stiffness, strength to weight ratio, high durability, high flexibility, optimization and customization options and many more. The popularity of composite materials in aerospace and aeronautical industry is hence increased. The continued use of composite materials in aircraft and aerospace industry will likely lead to further development of aircraft designs and performance in the future, causing the less use of traditional metals and more use of better performance based composite materials.

II. Use of Composite Materials in Ailerons of an Aircraft

The trailing edge of each fixed- wing aircraft wing frequently houses an aileron, an adjustable flight control surface. In order to control the aircraft's roll (or movement along its longitudinal axis), which often results in a change in flight path because the lift vector is skewed, pairs of ailerons are utilised. 'Rolling' or 'banking' is the term for movement about this axis. Commonly utilised materials include composites and aluminium.

F. Romano et.al (2009) tested with a full-depth aluminium aileron. To create CFRP aileron, method employed was RTM using dry fiber HTA 5131 and resin RTM6. By the time his study was finished, he had developed components that are net- shaped and closely tolerated, which maintain assembly costs and improve the weight to cost ratio while despite enabling multiple geometric designs [9]. Romano Fulvio et. al. (2004) proposed a multi-step process to design and analyse a composite material structure using fibre HTA 5131, matrix RTM6 with a target weight reduction of 14% relative to the metallic reference baseline. His study's findings indicated that a daily build pace would keep production expenses as low as feasible [10]. A. M. James and R. L. Vaughn (1976) spoke about composite aileron for commercial aircraft. Long term application to transport aircraft. Composite aileron for commercial aircraft with honeycomb sandwich covers. The sub structure consists of a hybrid of graphite/epoxy and Kevlar 49 structure passed test with no failure at 106% design ultimate load. With reference to this test load, the hinge lugs (lower lugs) will be subjected to a compression force of 5 398 kg and the hinge lugs to a tension load of 11 658 kg. Given that a fatigue test will be conducted on this specimen, this test was not run to failure [11]. Lalit K. Jain et. al. (1998) the thermoplastic composite material i.e, Carbon Fiber/Polyetherimide (CF/PEI) was employed by compression moulding; a spring-in model was used to work on attributes like the required processing temperature range. The spring-in model was effectively employed in the mould design and this resulted in good agreement between forecasts and experimental results. Microscopical analysis and void content measurement were utilised to identify the range of temperatures used in aileron rib compression moulding, which provided the data required by the spring-in model. [12].

RTM6: RTM6 is a monocomponent resin that is frequently used in the aerospace industry for resin transfer moulding process. RTM6 is a premixed epoxy-amine system, composed by the tetra-functional epoxy resin tetraglycidyl methylene dianiline (TGMDA) and two hardeners: 4,40-methylenebis (2,6-diethylaniline) and 4,40-methylenebis (2-isopropyl-6-methylaniline). RTM6 is developed for the resin transfer moulding process, and is characterized by an epoxy equivalent weight of 116 g/eq and a minimum viscosity of 33 mPa.s at 120◦ C. [13].

HTA 5131: The composition of HTA 5131, a PAN-based carbon fiber bundle used as reinforcement. [16].

Graphite and Kevlar 49 Fiber Hybrids: Graphite is a carbon-based material with high specific strengths and stiffness, yet it can be brittle. [19].

Polyetherimide: The Graphite and Short-Glass Fiber (GF) Filled composition has been examined for friction and wear qualities. [21].

As a result, we conclude that the choice of material is entirely dependent on cost, fracture toughness, tensile failure, density for weight maters and resistance. Because the Graphite and Kevlar 49 Fiber combination meets all of these requirements, it is proven to be the most superior of all the materials discussed above.

III. Use of Composite Materials in Wing Skin of an Aircraft

A An aircraft's skin is its outside covering, which mostly covers its wings and fuselage. The most frequently used materials are alloys of aluminium with other metals like zinc, magnesium, and copper as well as pure aluminium.

J.C. Ehrström et. al. (2022) tested Fibre Metal Laminate for wing skin, this material was manufactured using eight layers of 2024 T3 0.8 mm sheet and seven layers of glass fibre reinforced epoxy with a 0.25 mm thickness. This test aimed at validating the behaviour of a lower wing cover with a 1g stress (90Mpa for FML Cover), the test was done under constant amplitude loading. It shown that extremely lengthy inspection intervals and high levels of fatigue stress are achievable, and outcomes support an increase in 1g-stress permitted of 20% over bulk 2024 T351 and an inspection frequency of 45000 flights. [24]. Earlier in 2014, Marcin Ciesielski et. al. (2014) tested an Aluminium Alloy of Light High-Strength with a limited utilisation of steel and composite elements by the method of fractographic analysis. The specimen used as skin was made of D16CzATV aluminium alloy anodized. Test was carried out on PZL I-22 Iryda aircraft. The test determined that monitoring the crack's spread can be difficult as it often increases the gap in a constrained amount of time, between the rivet holes. The overload zones arise as moving on to the next load blocks and during the final fracture stage. If the stress severity factor is close to K1C, fracture surfaces with both dimples and striations are typical. [25]. M.M Ratwani et. al. (2002) tested a lower wing skin reinforced with Boron/Epoxy composite patch. The phosphoric acid non-tank anodize also known as PANTA procedure was employed to anodize the specimen's patch region during the validation test. The laminate was autoclaved for 60 minutes at 240◦ F and 90 psi of pressure to cure it. The surfaces corresponding to the inner and outer moldlines of the wing skin were determined to be of satisfactory quality, free of flaws, and to exhibit no bending in the centre of the specimen. Additionally, simultaneous gauges in the pocket's centre area display the same strains, showing there isn't any local bending in the area. Also, in contrast to the side without reinforcement, the strain gauge on the side of the composite reinforcement shows 60% greater strains. [26]. Furthermore, M. A. Mc Carthy et. al. (2004), conducted an impact test due to debris or bird strike on a wing skin panel. The test was conducted on Fibre Metal Laminate (Aluminium Alloy Layers and S2 Glass/Epoxy Layers). Using a hydraulic loading rig in stroke control, testing was performed at a strain rate of about 100 s-1. The results conclude that when compared to quasi-static loading, neither the final extension nor the tensile strength increased with medium rate loading. In this test, high strain rate effects that were blatantly obvious from coupon tests on the material are incorporated using a Continuum Damage Mechanics (CDM) model. The primary impacts seen in FMLs exposed to varying strain rates seem to be adequately represented by the CDM model. [27]. However, Karabin et. al. (2012) for lower wing applications Al-Li alloys can excel greatly. High levels of in-plane tensile gradients were challenges in the early stages of development oh Al-Li alloys like 2090, 2091, and 8090. Much research was done to address these issues, and today, the 2199 and 2060 plate products are manufactured to obtain uncrystallized microstructures which achieve great strength/toughness. [28].

Thus, it can be inferred that important parameters such high tensile strength, load carrying capability, structural integrity, and toughness factor may influence the selection criteria of materials for wing skin. Given the crucial factors described above, materials such as FML, Aluminium Alloys (D16CzATV), Aluminium-Lithium Alloys and Boron/Epoxy Composites are among the most frequently utilised ones for producing wing skins.

Fiber Metal Laminate (FML): Fiber metal laminates are created by bonding thin sheets of metal alloys, such as aluminium to fibre reinforced adhesives. The three types of fibre metal laminates (FMLs) that are most widely accessible on the commercial market are CARALL (Carbon Reinforced Aluminium Laminate), GLARE (Glass Reinforced Aluminium Laminate), ARALL (Aramid Reinforced Aluminium Laminate) which are based on Carbon, Glass and Aramids respectively. [29].

Alluminium Alloy: Alluminium Alloy plays a very significant role as a structural material for aircrafts, helping to create lighter airframes. High-strength alluminium alloys are used in manufacturing the key components like fuselage and wings, which have made it possible to design airplanes that can fly at high speeds and altitudes. [33].

Boron/Epoxy Composite: Adhesion-bonded fixes such as Boron/Epoxy composites, can effectively and affordably increase the endurance and damage tolerance of metallic surfaces that have fractures. The foundation of the repaired structures is the adhesive found in the adhesively linked patches. It has a major impact on the repaired structures integrity. [34].

Aluminium-Lithium Alloy: Al-Li alloy is an aluminium alloy with high elastic modulus, high specific strength and low density. It is outperformed by superior composites in terms of weight reduction and tensile strength but it has advantages over composites in terms of processing technology and the availability of pre-existing certification and qualification standards for materials, manufacturing processes and equipment's. Al-Li alloys are therefore acknowledged as the best structural material for lightweight parameters in the aircraft industry. [35]. Therefore, after a thorough comparison of the four potential materials for the wing skin of an aircraft, it had been determined that the Fiber Metal Laminate composed of Glass Fiber Epoxy and 2023 T3 Aluminium is the most appropriate material to use for the wing skin of an aircraft. It has crucial characteristics like high wear strength, excellent tensile strength, and an increase in ultimate tensile strength with ageing.

IV. Use of Composite Materials in Wing Spar of an Aircraft

Wing spars are an essential component of aircraft wings as they carry the majority of the load and must withstand various forces. Different materials are used for wing spars, such as aluminum alloys, steel. But the use of composites has proven to be more beneficial than the traditional metals.

Elangovan et al. (2018) tested different materials for wing spars, they applied a 1727 kg load on spar models of different materials and found that structural steel had the highest deflection, aluminium had the highest strain and high steel had the maximum stress [36]. However, Ambri (2018) suggests that aluminum alloys are the most commonly used material for wing spars due to their stiffness and high structural efficiency [37]. But composite materials have shown promise for wing spars due to their lower weight and comparable stress and strain characteristics compared to aluminium. Most common type of composite material is carbon graphite epoxy resin, Jacob Olaitan, Johnson-Anamemena et. al. (2017) tested LM, HM, and UM graphite epoxy wing spars for shear stress, bending moment, and deflection. Designs were observed to failed at 16801.8 N/2, which was higher than applied bending moment. UM graphite epoxy had least deflection (0.143 x 10-3 m), followed by HM and LM (0.185 x 10-3 m, 0.275 x 10-3 m). Results suggest UM graphite epoxy is suitable for spars. [38]. In addition, the application of a hardener can enhance the material's chemical and mechanical qualities, T. Kumaraswamy, Satish Nadakuditi et. al. (2016) found epoxy resin (LAPOX) with hardener K-6 to be more rigid than metal components. Composites formed had comparable durability to mild steel but were significantly lighter. Loading deflection graph on universal testing machine (UTM) showed stress of 77.1 N/mm2 and strain of 4.23 x 10-3 [39]. Ply sequence also plays an important role in increasing the stresses and strain values. A C-section spar with 13 layers was studied by Solovyev, Andrey Gomzin et. al. (2017). Finite element modelling showed that a unidirectional structure (0°) n is optimal for stiffness, while a structure with (0°/90°) m /0°/ (0°/90°) m is recommended for stress state risk. The study focused on polyimide matrix and carbon ribbon composites [40]. Additionally, the optimization of wing spar can also help in increasing parameters. The research paper by Phyo Wai Aung, Oleg Tatarnikov et. al. (2020) enhanced the structure of a composite wing of a light aircraft by optimizing the wing design. The optimized wing design reduced weight while maintaining its physical properties. Optimal structural parameters for the front spar, rear spar, and ribs were determined, with a unidirectional arrangement of plies (0°) for spars as the optimal laminate structures. The deflection as found to be 32.45 mm [41]. Additional studies were conducted by making structural changes in wing spar to check the strength and stiffness of it, Clément Fleuret, Anne-Sophie Andreani et. al. (2016) used carbon-epoxy composite (TR50 carbon fibres and R367-2 epoxy matrix) with C70-75 PVC foam core and titanium pins for a four-point bending load test. Severe punching was observed under light load in the first test, but new tools allowed for larger loading (30,000 N) without damage in the second test. Average maximum stress in the flange was 700 MPa [42]. Gokulnath R et.al. (2018) applied 15KN load to cantilever beams with varying hole diameters made of glass, carbon, and glass-carbon epoxy fibres. Epoxy beams showed higher resistance than glass fiber epoxy beams. Carbon epoxy fiber experienced higher tensile stress and stress concentration factor than glass epoxy fiber, but had lower displacement under tensile load with larger cut-out diameter [43].

Carbon graphite/fibre epoxy resin: Carbon graphite/fibre epoxy resin composite are extensively utilised in aeronautical applications particularly for constructing aircraft wing spar. The combination of high strength carbon fibres and lightweight epoxy matrix yields a material with exceptional strength to weight ratio. The carbon fibre provides excellent tensile strength and stiffness, while epoxy resin matrix enhances durability and resistance to environmental factors. This advanced composite material exhibits superior fatigue resistance, crucial for the cyclic loading experienced by wing spars during the flight. The anisotropic nature of carbon fibres allows for tailoring the properties in specific directions, optimizing structural performance.

Glass Fibre reinforced composites: Glass fiber reinforced composites, commonly known as fiberglass composites, are materials widely used in the aeronautical industry, particularly in the construction of wing spars. These composites consist of glass fibers embedded in a matrix, typically made of epoxy resin, offering durability and protection.

Hence, the choice of material for a wing depends on the required properties such as stiffness, weight, strength and durability. In conclusion, the diverse studies on wing spar materials highlight the evolving landscape in aircraft design. While traditional metals like aluminium alloys remain prevalent, the ascendancy of composite materials, like carbon graphite/fibre epoxy resin, glass fibre reinforced composites, is evident. TR50 Carbon Fiber with R367-2 Epoxy matrix noticed to be the superior of the two materials.

Table no 1: Significance of the potential materials that can be used in the aerospace industry.

Materials	Advantages	Disadvantages
RTM 6	Exhibits a high glass transition temperature, which ensures dimensional stability and resistance to high temperatures. [14].	Mass loss during the infusion of RTM6. [15].
HTA5131	High tensile strength, stiffness, and resistance to corrosion and high temperatures. [17].	Composites under transverse loading the interfacial normal strength governs the initiation of failure. [18].
Graphite and Kevlar 49 fiber Hybrid	Composites Strikes a balance between carbon fiber's high modulus and Kevlar's impact resistance. [20]. Exhibit greater fracture toughness and tensile failure strains. [20].	Faces challenges in component design due toa mismatch in Young's modulus. [20]. Load carrying capacity of the glass fiber is limited before the carbon fiber fails. [20].
Polyetherimide	Amorphous, High-performance engineering thermoplastic. [22]. Low moisture absorption. [22].	Acid treatment causes erosion and permanent structural and chemical changes in polymeric materials, as well as the formation of flaws in carbon nanotubes. [23].
GLARE (Glass Fibre & 2024 T3 Aluminium)	High tensile strength. Excellent wear strength. [30].	Decrease in shear strength after thermal cycling tests. [31].
Al Alloy	Increase in ultimate tensile strength with ageing. [32]. Ease of fabrication, including casting, forging and heat-treatment. [33]. Ductility, fracture toughness and fatigue resistance. [33].	Decrease in toughness with ageing. [32]. Low mechanical properties at elevated temperature (softening occurs above ~150 °C). [33]. Age-hardenable alloys cannot be easily welded. [33].
Boron/Epoxy Composite	Provides considerable increase in residual strength. [34].	-
Al-Li Alloy	Increase in cooling rate can improve tensile properties. [35].	Low tensile strength due to porosity. [35]. Poor ductility. [35].
Carbon graphite/fibre epoxy resin	Higher Flame retardancy as compared to traditional material. [44]. Improved toughness and mechanical properties like elevated shear and flexure resistance. [45].	Delamination of layers can occur. Prolonged exposure to UV radiation can degrade the material properties [45].
Glass Fibre reinforced composites	High strength with significantly lower weight, hence, contributing to improved fuel efficiency and overall aircraft performance [46]. Exhibit excellent corrosion resistance. [47].	High initial cost, also, they can be brittle [47].

V. Conclusion

Combining two materials with distinct chemical and physical characteristics creates a composite material. When combined, they provide a material with improved mechanical properties including increased strength, lighter weight and increased efficiency. Hence the aerospace and aeronautical industries have moved their focus from employing traditional materials to using composite materials. In this study, after a thorough comparison we conclude that the suitable material for an aileron of an aircraft is the combination of Graphite and Kevlar 49 Fiber which provides toughness and strength and also is a cost-effective material. For an aircraft's wing skin, the appropriate material is Fiber Metal Laminate composed of Glass Fiber Epoxy and 2023 T3 Aluminium due to its characteristics such as excellent wear strength and tensile strength. Ultimately, for the wing spar TR50 Carbon Fiber with R367-2 Epoxy matrix is the most suitable material due to its properties like stiffness, weight, strength and durability.

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