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FIBER-REINFORCED POLYMER COMPOSITES AS STRUCTURAL MATERIALS FOR AERONAUTICS

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Abstract: *Composite materials based on fiber-reinforced polymers are becoming preferred materials for aircraft and spacecraft construction. Their use as structural materials in recent years has proved their advantages. This paper offers an overview of several applications in aeronautics, but it focuses on composites application as structural materials, due to the fact that they have recorded a significantly increased use. The nature of composite materials and their behavior under specific stress, special problems in design and preparation, as well as issues connected with their impact damage and damage tolerance, environmental degradation and long-term stability, are presented in this report.*

Keywords: *composites, structural materials, aeronautics*

1. INTRODUCTION

Aeronautics engineering is changing [1,2,3]. Planes have traditionally been made out of metals – usually, aluminum and its alloys, steel, and titanium alloys. Nowadays, engineers are increasingly working with carbon fiber composites. Fiber-reinforced composite materials were originally used in small amounts in military aircrafts during the 1960s, and within civil aviation from the 1970s. By the 1980s, polymer composites were being used by civil aircraft manufacturers for a variety of secondary wing and tail components (such as rudder and wing trailing edge panels).

The latest generation of airliners, such as the Airbus A380, the world’s largest passenger aircraft, shows that these composite materials have been employed extensively in the primary load carrying structure: A380 uses composite materials in its wings, which helps enable a 17% lower fuel use per passenger than other comparable aircraft [2], whereas the newest Boeing, the 787 Dreamliner, has the highest content of composites (Figure 1) 50% (http://www.newairplane.com/787).

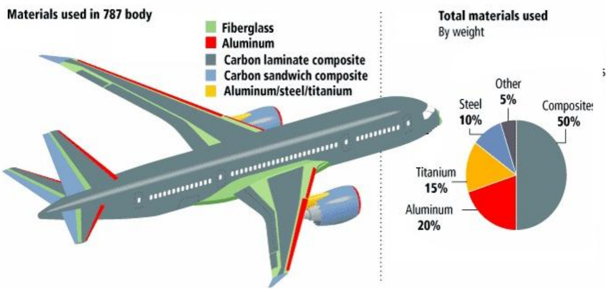


Figure 1. Use of composites in the structure of Boeing 787 Dreamliner (www.boeing.com)

Fiber-reinforced polymer composites can provide a much better strength-to-weight ratio than metals, sometimes by 20%. The lower weight results in lower fuel consumption and emissions, enhanced aerodynamic efficiency, lower manufacturing costs. The aviation industry was the first interested in such benefits and it was the manufacturers of military aircrafts who initially seized the opportunity to use composites characteristics to improve the speed and maneuverability of their products.

In the last four decades, the aerospace sector underwent a series of changes in terms of composites implementation in aircraft and helicopter production. Fiberglass composites were the first to be used by the aerospace industry, followed by two other composites, *i.e.* carbon fiber and aramid fiber, added in the early 1970s. The main applications of composite materials for helicopter and aircraft interior design include the fabrication of instrument panels, fuselage skin panels, and fuselage fairing panels. Some of the main advantages of using composite materials are the relatively low fabrication and installation costs, as well as lower toxicity and increased resistance to fire.

One great innovation in the field of composite materials for aeronautics is the ability to produce complex parts in one piece, particularly through thermoforming, which will enable reduced costs related to machining and to component assembly. Research provided a reliable database for the development of composites, so that enabled parts to be designed with unique physical and chemical properties for specific use and to meet the specific needs of the industry. Besides offering the opportunity to design durable and resistant parts, fiber-reinforced composites have the advantage of providing excellent resistance to corrosion.

2. COMPOSITES AS STRUCTURAL MATERIALS IN AERONAUTICS

2.1 Aeronautics features. Whether it is a single engine private plane, a giant commercial airliner, or a supersonic fighter plane, aircrafts are the work of engineers. Specific structures in aeronautics have to meet characteristic requirements, such as safety standards (special demands of fire-retardancy [4] and crashworthiness [5-7]), fuel sealing, easy access for equipments maintenance; vacuum, radiation and thermal cycling has to be considered and special materials are required to be developed for durability.

Two major directions of research in this field had a significant influence on the development of new generations of materials and, hence, aircrafts: advances in the computational sciences, generating powerful computational tools, as well as CAD modelling and computer interfaces in manufacturing, and the progress of the composites technology using fibre-reinforced polymeric materials as structural materials for aeronautics. Some requirements of an aircraft structure are presented in Table 1, as well as design demands arising from them [8].

Table 1. Aircraft requirements and subsequent design demands

Requirement	Design demands	Obs.
Low weight	Semi-monocoque construction Thin-walled-box or stiffened structures Use of low density materials: wood, Al-alloys, composites High strength/weight ratio, high stiffness/ weight ratio	Application area: all aerospace programs
High reliability	Strict quality control Extensive testing for reliable data Certification: proof of design	Application area: all aerospace programs
Passenger safety	Use of fire retardant materials and coatings Extensive testing: crashworthiness	Application area: passengers transport
Aerodynamic performance	Highly complex loading Thin flexible wings and control surfaces Deformed shape: aero-elasticity, dynamics Complex contoured shapes: processability, machining, moulding	Application area: all aerospace programs
Stealth	Specific surface and shape of aircraft Stealth coatings	Application in military programs
All-weather operation	Lightning protection, erosion/corrosion resistance Corrosion prevention schemes Issues of damage and safe-life, life extension Extensive testing for required environment Thin materials with high integrity	Application area: all aerospace programs

2.2 Specific requirements for polymer composites used in aeronautics. The use of advanced fiber-reinforced polymer composites in aeronautics has been conditional upon their properties given by both fillers (carbon or aramid fibers) and matrices [9]. Their combined characteristics granted them lightweight, due to high specific strength and stiffness, fatigue and corrosion resistance, availability towards optimization (*e. g.*, tailoring the directional strength and stiffness), enhanced processability (ability to mould large complex shapes in short time cycles, reducing part count and assembly times), time and place stability, low dielectric loss, achievable low radar profile and stealth availability, etc.

Still, despite all these advantages, these composites have a few flaws: some of the corresponding laminates display weak interfaces adhesion, yielding in poor resistance to out-of-plane tensile loads; susceptibility to impact-damage and strong possibility of some internal damages evolving unnoticed; moisture absorption and consequent degradation; occurrence of possible manufacturing defects.

Nowadays, the use of advanced composite materials has been extended to a large number of aircraft components, both structural and non-structural, based on various factors. Some details from civilian and military aviation [10] are presented in Table 2 and 3.

A realistic approach indicates that estimated benefits, especially when it comes to the new generations of composites [11], are significant and almost all aerospace programs use increasing amounts of composites. Hence, it is necessary to take into consideration the complex behavior of these materials, since they are anisotropic and inhomogeneous, have different fabrication and processing requirements, and need different control methods, new and complex analysis protocols for quality assurance. Moreover, their behavior is not always predictable which makes reliance on several expensive and time consuming tests mandatory.

Table 2. Use of composites in Airbus and Boeing series

Aircraft type	**Parts and components**	**(%)**
Airbus A300B2/ B4	Radome, fin leading edge and tip, fin trailing edge panels, cabin and cargo hold furnishings. Fairing -pylon, wing/ fuselage rear.	5
Airbus A310-300	Rudder, elevator, vertical stabilizer, spoilers, cowl (inlet & fan), thrust reverser, main & nose landing gear door of wing leading & trailing edge panels, nacelles. Fairings -Ion, flap track, win fuselage.	7
Airbus A320/A319/A321	Aileron, horizontal and vertical stabilizer, elevator, rudder, spoilers, flaps, engine cowl, radome, landing gear doors (main & nose), floor panels, wing panels (leading & trailing edge), other access panels, nacelles. Fairings-flap track, wing/fuselage (forward & rear), main landing gear leg.	15
Airbus A330	Ailerons, rudder, flaps, spoilers, elevator, horizontal and vertical stabilizer, wing panels (leading & trailing edge), landing gear doors (main & nose), nacelles. Fairings -flap track, wing/fuselage (forward & rear).	12
Airbus A340	Ailerons, rudder, flaps, spoilers, elevator, horizontal and vertical stabilizer, wing panels (leading & trailing edge), landing gear doors (main & nose), nacelles. Fairings -flap track, wing/fuselage (forward & rear).	12
Boeing 737 (200, 300, 400)	Spoilers and horizontal stabilizer (both limited production), trailing edge flaps. Aileron, elevator, rudder, nacelles. Aileron, elevator, rudder, nacelles.	<1 3
Boeing 747-400	CFRP winglets and main deck floor panels. CFRP and AFRP used in cabin fittings engine nacelles.	3
Boeing 757	Aileron, elevator, rudder, spoilers, flaps (in-board & outboard), fairings and nacelles.	3
Boeing 767	Ailerons, elevator, rudder, spoilers, landing gear doors (nose & main), fairings and nacelles.	3
Boeing 777	Ailerons, elevator, rudder, spoilers, flaps (in-board & outboard), floor beams, landing gear doors (nose & main), fairings and nacelles.	10

These challenges can be met by using the advances in computer technology and analysis methods to implement schemes based on computer aided design, computer aided engineering, finite element methods of analysis.

Table 3. Use of composites in military airplanes and helicopters

Aircraft type	Parts and components
F-14	Doors, horizontal tail and fairings
F-15	Rudder, vertical tail, horizontal tail, speed brake
F-16	Vertical tail, horizontal tail
F-18	Doors, vertical and horizontal tail, fairings, wing box, speed brake
B-1	Doors, vertical/horizontal tail, flaps, slats
AV-8B	Doors, rudder, vertical tail, horizontal tail, aileron, flaps, wing box, body and fairings
Typhoon	Wing, fin, rudder, in-board aileron, fuselage
LCA	Wing, fin, rudder, control surfaces, radome
MBB BK 117	Main rotor blades, tail rotor blades, horizontal stabilizer, vertical stabilizer
Bell 206L	Vertical stabilizer
Bell 402	Main rotor blades
Dauphin	Main rotor blades, vertical stabilizer
McDonnell Douglas MD 520N	Main rotor blades, tail boom
McDonnell Douglas MD 900	Main rotor blades, fuselage mid section, tail boom, canopy frame, internal fuselage, horizontal stabilizer, vertical stabilizer
ALH	Main & tail rotor blades, rotor hub, nose cone, crew & passenger doors, cowling, most of the tail unit, lower rear tail boom, cock it section

Thus, the entire process is computer assisted, from design and analysis up to manufacturing, enabling the fast transfer of information and accurate analysis methods for a reasonable prediction of composites complex behavioral patterns [8].

2.3 Reliability and safety issues. Fiber-reinforced polymer composites used in aeronautics have to meet reliability and safety issues, which requires testing at all stages (design and development, proving and certification, in-service inspection and repairs), due to the composites complex behavior and difficulty in creating predicting models. Additional operations are reflected in increased final costs.

Safety issues - risk-based approaches and tools have been developed by the aeronautic communities, especially by the military, to ensure aircrafts availability and to reduce costs while maintaining structural safety [12-15].

Impact damage and damage tolerance – some composites laminates made of fiber-reinforced polymers are characterized by weak interfacial interactions (due mostly to a certain incompatibility between matrix and filler) and this favors phenomena as delamination or debonding under stress [16].

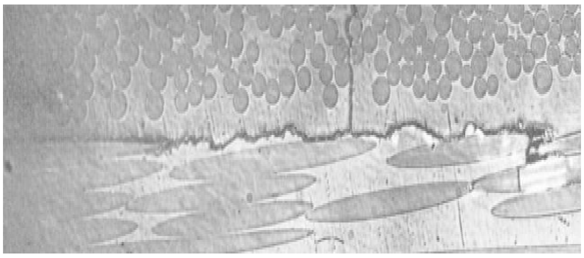


Figure 2. In many types of composite structures (e.g. aircraft, marine, etc.), delaminations are the most common form of defect/damage

Even more, when discontinuous plies (made to create thickness changes) or sharp bends (required in stiffening pieces) are used for structural features, these phenomena are more intense, especially when it comes to damages at impact because they might not be evident in initial stages, but worsen under prolonged stress. This behavior occurs in case of impact with blunt objects at low to medium velocity (accidental dropping, hail, debris, shocks even before the aircraft assembly, or even a bullet impact which, in the case of a fuel tank, will cause a hydraulic ram effect in the fuel, leading to explosion). These flaws may occur not only in 2-D, but they can propagate through the entire thickness, mainly when micro-cracks emerge in back plies or other hidden stress concentrators, detectable by ultrasonic C-scan method. It is possible to limit effects of these damages by combining various approaches: (1) design (structures with alternate load paths) [17], (2) setting lower allowable stress values and (3) defining new inspection intervals and protocols. Damage tolerant structures are designed to sustain cracks before failure occurs, so that the defect is detected in and the damaged part is repaired or replaced (Figure 3). In addition, damage tolerance takes into account initial material or manufacturing flaws by assuming an initial crack, which the fail-safe principle does not do [18].

Humidity is causing weight gain in most fiber-reinforced composites, no matter whether the matrix is a thermoset or thermoplastic polymer. Under the normal operating conditions, the maximum equilibrium moisture gain in an aircraft component can be 1.0-1.4%.

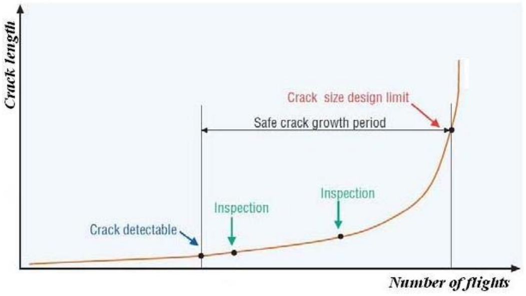


Figure 3. Theoretical damage tolerance inspection regime to detect cracks before they become critical

This may cause swelling and dimensional changes, lowering the glass transition temperature (Tg) of the matrix, as well as a decrease of shear and compression strength.

The diminution of the shear and compressive strength is a major concern in aircraft structures, mainly at high temperatures close to Tg, because polymers Tg is decreasing due to the moisture sorption. Therefore, the design of a structural component proceeds, generally, by reducing allowables for moisture degradation. As a general observation, the dimensional changes and weight gain are not significant in many aircraft structures, but they may be of considerable significance where extreme precision is required, such as in antennae panels and in satellite structures.

Significant issues relate to the UV degradation and radiation effects in long term exploitation, especially for spacecrafts structures. Current studies have provided some solutions.

3. FIBER-REINFORCES POLYMER COMPOSITES USED IN AEROSPACE INDUSTRY

3.1 Background. Advanced research enables scientists and engineers a better understanding of how to use fiber-reinforced polymer composites as structural materials for aerospace industry, but studies also encompass the interactions of the structure with the aircraft system as a whole. Aero-elastic tailoring is one example of such interaction. On another hand, by developing standard tools to test the potential performance of composites, there are possibilities to increase the use of composites in other leading industries.

3.2 Fibers as reinforcement. Carbon fiber reinforced plastics (CFRPs) – used for the first time during the 1960s - owe their high structural performance to the exceptional properties (low density, high thermal conductivity and excellent mechanical properties at elevated temperatures) of the individual strands. By way of comparison, the ultimate strength of aerospace grade aluminum alloys is 450MPa, whilst that of a carbon fiber would be five times higher. Glass, aramid and boron (far superior to carbon fibers, but 6 times more expensive) fibers are also used, but it seems carbon fibers have the best strength/cost ratio for primary load-bearing structure. The carbon fibers technology continues to improve by valorizing the versatility of carbon fibers and new varieties with improved modulus and strength are available. A comparison between fibers used as reinforcement in aeronautics is presented in Table 4 and a synthetic review of aramid fibers commercially available is shown in Table 5.

Two directions of development seem to be concerned:

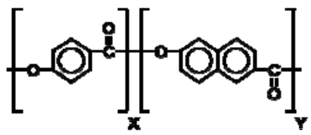
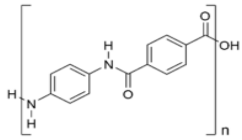
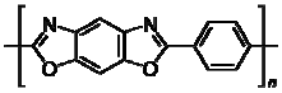
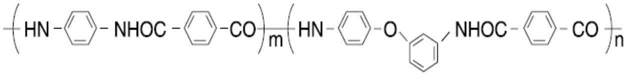
(1) aircraft applications - higher strength (>5 GPa) concurrent with improvements in modulus to moderate levels (>300 GPa) and

(2) space applications - high modulus (>500GPa) along with moderate strength (~3.5 GPa). The development in aramid fibers is also aiming at higher modulus concurrent with increased strength.

Table 4. Reinforcing fibers used in aerospace industry

Fibers		Density (g/cm^3)	Modulus (GPa)	Strength (GPa)	Application
Glass	**E-glass**	2.55	65-75	2.2-2.6	Small passenger aircraft parts, radomes, rocket motor casings
	S-glass	2.47	85-95	4.4-4.8	Highly loaded parts
Aramid (modulus)	**Low**	1.44	80-85	2.7-2.8	Fairings; unloaded bearing parts
	Intermediate	1.44	120-128	2.7-2.8	Radomes, some structural parts; rocket motor casings
	High	1.48	160-170	2.3-2.4	Highly loaded parts
Carbon (modulus)	**Standard**	1.77-1.80	220-240	3.0-3.5	Widely used for almost all types of parts, satellites, antenna dishes, missiles, etc.
	Intermediate	1.77-1.81	270-300	5.4-5.7	Primary structural parts in high performance fighters
	High	1.77-1.80	390-450	2.8-3.0 4.0-4.5	Space structures, control surfaces
	Ultra-high	1.80-1.82	290-310	7.0-7.5	Primary structural parts in high performance fighters, spacecrafts
Boron	**3-; 4-; 5.6-mil Boron**	2.38-2.54	380-400	3.6-4.0	Structural reinforcement; thermal and radiative deflectors

Table 5. Aramid fibers used in aerospace industry

Name	Structure	Applications
VECTRAN		Advanced composite materials used by NASA's Extravehicular Mobility Unit and for all of the airbag landings on Mars: Mars Pathfinder in 1997 and on the twin Mars Exploration Rovers *Spirit* and *Opportunity* missions in 2004, as well as for NASA's 2011 Mars Science Laboratory in the bridle cables.
TWARON		Reinforcement in composite parts such as fairings and airfreight containers, containment belts used in turbine engines to protect the passenger compartment in case of engine failure.
ZYLON		Zylon is used by NASA in long-duration, high altitude data collection. Braided Zylon strands maintain the structure of polyethylene superpressure balloons.
TECHNORA		Suspension cords for the strongest and largest supersonic parachute used by NASA for Curiosity Rover.

However, the major improvement for composite reinforcements is the multidirectional weaving. Several processes (weaving, knitting, braiding) have been developed for this purpose and prepregs with multidirectionally woven fibers have been obtained. Significant advances based on the translation of high fibers properties into high performance composites are envisaged, but costs reduction and environmental protection are also aimed.

3.3 Polymer matrices. A remarkable effort in improving composites is focused on improving matrix polymers. The two major concerns mentioned earlier, impact damage tolerance and hydrothermal degradation, provide the main motivation. A major direction of improvement appears to be in the toughness which should result in higher resistance to delamination and impact. High failure strain of matrix polymer would help in translating the higher performance of the improved fiber to the entire composite. Higher shear modulus polymers will achieve better transfer of load from fiber to matrix and again to fiber, therefore improving the compression strength. It is possible for polymeric materials to achieve moduli of approx. 5 GPa, since the current matrices have shear modulus values of about 2 GPa. As far as hygrothermal degradation is considered, newer systems based on cyanate esters look very promising and some of these have already found application.

Another route being investigated is the use of thermoplastic polymers [26-31] and their blends. Poly-ether-ether-ketone (PEEK) has been considered very promising, but the industry needs to resolve the problems associated with high temperature (> 350°C) processing of the material. Other promising new matrices are temperature-resistant polymers, such as polypropylene (PP) [28,29], polyphenylene sulphide (PPS) [30], polymethacrylimide (PMI) [30], polyvinyl chloride [30] and their derivatives and blends.

A polymer with excellent properties is PrimoSpire® SRP (self reinforced polyphenylene) by Solvay [32]: tensile properties that are comparable to those of many reinforced plastics (Figure 4), lighter weight and no loss of ductility, high compressive strength – one of the highest among plastics.

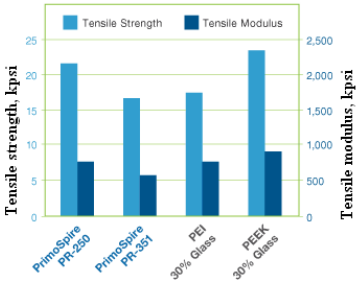


Figure 4. Tensile properties of PrimoSpire® SRP

Due to these characteristics, it is an excellent candidate for weight-sensitive applications that also require superior mechanical performance.

Current approaches appear to be directed towards producing polymeric systems which can be processed in conventional ways. Two promising classes of such materials are under development:

(1) polymerizable liquid crystalline monomers that should result in thermoset resins having high fracture toughness and Tg=170°C, and with high degree of retention (=90%) under hot-wet conditions; compared to thermoplastic PEEK, such matrix will have almost similar fracture toughness along with the advantage of conventional processing. The approach for the development of these new polymers is to synthesize, first, controlled molecular weight backbones consisting of aromatic ethers, esters or rigid aliculic systems [8] with hydroxyl end groups and then to end-cap them with reactive end groups like cyanate ester group or glycidyl ethers.

(2) phthalonitrile resins for high temperature applications which can be cured in conventional manner (at 180-200°C), but can be also post-cured, albeit in inert atmosphere, at high temperatures up to 600°C. Compared with the current resins synthesized by polymerization of monomer reactants for high temperature (250-350°C) applications, the new resins will have better processability, good fracture resistance, better strength and modulus, and very low moisture sorption.

The other area of advances in matrices research is the of low-loss polymers, especially for radomes which use high-performance radars. Different low-loss polyesters and cyanate esters are under study.

4. FUTURE DEVELOPMENT

4.1 Nanoparticles. Fiber-reinforced polymer composites for aeronautics may be further developed by the use nanofillers such as electrospun carbon nanotubes and nanofibers, electrospun silica nanofibres. Adding small amounts of carbon nanotubes (CNTs) (0.15%) to a tetraethyl orthosilicate matrix, obtained *via* a sol-gel process, will yield in composites with CNTs binding directly the adjacent layers. The electrically charged nanoparticles would bind directly to adjacent plies, each given an electrical charge in advance, to allow binding of the oppositely charged nanoparticles. This would create a "velcro" effect which will reduce reliance on the binding properties of the matrix, producing composites with enhanced strength, more impact resistant and lighter than those known today.

Great opportunities for carbon nanofibre patches are envisaged for advanced repair of composite structures. Such patches would increase the contact surface available for bonding and reduce the need to delaminate additional areas in order to repair a delaminated zone of the structure.

4.2 Ceramic matrix composites and metal matrix composites are two other groups of composites able to respond to aerospace industry demands. Ceramic matrix composites (CMCs) made of silicon carbide fibers in a silicon carbide matrix are of great interest for low-pressure turbine blades, pre-combustion mixer of engines and, potentially, the high-pressure core of the engine.

In he case of metal matrix composites (MMCs), the research is still in the beginning, but it is already predicted that these materials, which will use carbon or metal nanotubes to strengthen metal matrices, will have twice the strength of comparable existing metal structures, but only 2/3 of their weight. Such materials would be ideal for engine tie rod struts which transfer the engine thrust into the airframe.

Other directions for the future development of the domain: study of properties of composites with basalt or clay particles, electrospun silica nanotubes, etc.

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