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A SURVEY ON COMPOSITE APPLICATIONS IN AEROSPACE ENGINEERING AND MANAGEMENT OF ASSUMED RISKS IN CASE OF DAMAGE TOLERANCE

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Abstract:

The intent of this paper is to present the most important applications of composite materials in aerospace engineering, that can be related to aerostructures, jet engines parts such as fan blades, wind turbine blades, and most often used the Vertical Axis Wind Turbine (VAWT). Last but not least, are the applications of composites to other industries, which can be related to the environmental impact as ground vehicles or industries relatable with human care and wellbeing, e.g. reconstructions of damaged human body parts, prosthetics, and dentistry. The use of composites, in aerospace engineering, provides a significant reduction of costs for manufacturing, technology, and operation, provided adequate management. Management in composites manufacturing and technology may allow the achievement of performance and cost-effectiveness for the most significant products, as aerostructures, fan blades, VAWT blades are.

Keywords: composite materials, aerostructures, jet engine parts, fan blades, wind turbine blades.

1. INTRODUCTION

Composite materials represent a very promising option that allows the obtaining of product performances and constituent properties, cost-effectiveness, adaptability as the ability to enable geometrically accurate design and manufacturing of 3D bodies with complex geometry, flexible customized design with the ultimate goal to enable the matching of structural behavior such that to withstand the required loads and stresses, in compliance with the military and civil aerospace engineering regulations for damage resistance, durability and damage tolerance. The recycling possibilities can significantly reduce costs and generate a strong potential for mitigating the environmental impact.

The advantages of using composites are expressed by the high ratio of strength to weight, low thermal expansion coefficient (CTE), excellent behavior due to fatigue properties, very good corrosion resistance, and flexibility in custom design of laminates, depending on the profile and time dynamics of loads during the life cycle.

A direct consequence is the strong reduction of the number of components. The result of cutting the number of fasteners, as aerostructure critical components, due to the continuous increase of using composites is shown by the comparison between B 747 and B 787, see Figure 1, [1].

(a) - B 747, 1 % composites, 1M fasteners

(b) - B 787, 50 % composites, < 10K fasteners

Fig. 1 – The result of increasing the % use of composites versus reducing the number of critical component parts, [1]

The most important applications of composites are related to aerospace, wind, and automotive engineering. Also, the most significant applications, of composite materials in aerospace engineering that can be related to aerostructures jet engines parts are: fan blades, fuel tanks for liquid-propellant rocket engines, wind turbine parts, such as blades; the Vertical Axis Wind Turbines are mostly used.

The use of composites is not limited to the field of aerospace engineering, but can be successfully used in transportation: aircraft Fig. 2-a, automotive Fig. 2-b, water vehicles Fig. 2-c, wind power engineering Fig. 2-f, and other industries, which can be related with the environmental impact, as ground vehicles or industries relatable with human care and wellbeing, e.g. reconstructions of damaged human body parts, prosthetics and dental reconstruction Fig. 2-e, as well as, sporting goods Fig. 2-d and musical instruments.

(a) – aircraft (e.g. B787)

(b) – vehicles

(c) - yachts

(d) – sporting goods

(e) – dental reconstructions

(f) – wind turbines

Fig. 2 – Different use of composites, [2]

2. PRELIMINARIES ON COMPOSITES USED IN AEROSPACE ENGINEERING

The performances of aircraft and space product applications are influenced, to a great extent, by the structural weight that represents a critical parameter. Therefore, the need for decreasing the structural weight eventually led to the development of composite materials, and especially high-performance composite materials, which consist of carbon fibers and epoxy resins. The objectives of the high-performance composite materials are to provide higher specific strength and stiffness, with compulsory compliance with the high safety standards, specifically in the commercial aircraft industry and even more demanding in the military aircraft industry.

The composite materials structure can be defined as a customized net, of fibers embedded, in a matrix of resins, which enables the elastic behavior. The composites' construction can be either single-layered or multiple-layered. The materials used, for the net of fibers, can be fiberglass, carbon, boron, Kevlar, or Spectra. The materials used for the elastic matrix can be epoxy, vinyl ester, bismaleimide, polyimide, or polyester. Other materials, having potential for use in composites, as monolithic metal structures and lower cost composites, such as wood, foam cores, and reinforced concrete, can be considered for general applications.

The advantages, provided by the use of composite materials, compared to other conventional isotropic aircraft materials, such as aluminum alloys, titanium alloys, and steel, are expressed by specific strength and stiffness gained due to high-performance fibers. Composite materials do not face the issue of galvanic corrosion, as in the case of the aluminum alloys, nor do they require high inspection and maintenance costs, due to fatigue as the metallic structures do.

Fig. 3 – An example of multiple layered composite structure, [3]

3. APPLICATIONS OF COMPOSITES IN AEROSPACE ENGINEERING AND DEVELOPMENTS

For the reason of the compliance with the safety standards specifically stated in regulations for the commercial and military aircraft industry, the composite materials were gradually introduced in aircraft and space product constructions.

Fig. 4 – Use of composite materials on aircraft, [4]

The use of composite materials in modern aircraft is detailed in Fig. 4 for the main parts,

like: 1/ fan, propellers, rotor system, 2/ aerostructure: 2.1/ fuselage, 2.2/ wings, 2.3/ empennage, 2.4/ flight control surfaces (i.e. flaps, elevator, ailerons), 3/ engine components, 4/ nacelle and pylon, 5/ systems.

From the historical standpoint, the introduction and implementation of composite materials in the aircraft industry were done gradually, so that several phases could be recorded, depending on the damage tolerance and the compliance with the safety standards, stated for the commercial and military aircraft industry.

The milestone which marks the beginning of using composites in the aircraft industry can be associated with the Boeing 707 and DC-9 aircraft, in the late 1950s.

In the first phase, the implementation of the composite materials included only tertiary components, such as interior parts, sidewalks, bag racks, and galleys. Their failure in operation would not affect the aircraft's flying capabilities.

In the second phase of the implementation, composite materials were introduced for secondary aircraft structures, such as spoilers, rudders, ailerons, and flaps, after the 1960s.

Thereby, after the 1970s, fiberglass was retained for many interior parts and fairings, while for the secondary aircraft structures (i.e. spoilers, rudders, ailerons, and flaps) fiberglass was replaced by carbon fibers.

The third phase is the implementation of the composite materials, within aircraft primary structures, such as stabilizers, wings, and fuselage barrels. The design and use of carbon fibers and boron fibers, initiated for military aircraft and expanded to commercial aircraft, for flight control surfaces (i.e. rudders, flaps) to stabilizers, wings, and fuselage structures. In Fig. 5 are presented aircraft like AV-8, B-2, F/A-18, Eurofighter, AH-66 as representative examples for the second phase of the implementation of the composite materials.

The first high-performance composite materials implementation for primary structures was done in the 1980s for the B 737 horizontal stabilizer, which was followed by thorough testing and in-flight evaluations.

The next phase is represented by the design, development, and the implementation in production of the composite materials for vertical and horizontal stabilizers, customized in purpose to achieve lightweight structures and improved aircraft performances.

(a) - body structure

Fig. 5 – Materials used in B 787 Dreamliner, [7]

The completion phase consists of expanding the implementation of high-performance carbon fiber composite materials to the stabilizers, wings, and fuselage. Another gained advantage is the significant decrease of the aircraft weight, since the stabilizers, wings, and fuselage taken together represent about 50% of aircraft structural weight. A representative example of the new generation of commercial aircraft is the B 787 “Dreamliner” aircraft.

Fig. 6 – Evolution of the use of composites in aerostructures [5]

The components of the B 787 “Dreamliner”, which use composite structures, are: 1/ fuselage – almost full-body, 2/ upper and lower wing skin, 3/ radome, 4/ flight control surfaces (i.e. wing flaps, elevators, ailerons), 5/ vertical fin, 6/ horizontal stabilizer, Fig. 5. The current phase corresponds to the increased use of composite materials on both military and commercial aircraft.

(b) – Improvements of structural aluminum alloy

Fig. 7 – Lessons learned from the experience of Boeing aircraft, [5, 6]

The evolution of the use of composites in aerostructures, Fig. 6, has registered a % increase of composite materials, followed by steel and titanium alloys, compared to the decline in the use of aluminum alloys and other metals, Fig. 7-a; nevertheless, improvements of structural aluminum alloy, Fig. 7-b, continued to be developed.

(a) – B 767

(b) – B 757

Fig. 8 – Development of composite materials implementation on Boeing aircraft, [7]

The implementation of the use of composites in the aircraft industry has been gradually done, according to the validation of custom design composite parts, based on matching the capability to overcome loads and stresses, with the compliance to the safety standards stated, in the regulations of the military and commercial aviation. The development of composite materials implementation on Boeing aircraft is detailed in Fig.8-a, b, and Fig.9-a.

(a) – B 777

(b) – Improvements from B707 to B747 and B777

(c) – Improvements from B707 to B747 and B777

Fig. 9 – Development of composite materials implementation on Boeing aircraft, [7]

The combination of new construction design (e.g. nacelle and pylon, B 707 versus B 777, improved B 747-8 wing design) with the expanding the use of composites on aircraft (B 747 versus B 777), Fig. 9-b/c, is the key element to provide improved product performances (higher specific strength and stiffness introduced by composites, which enabled lighter aircraft, more powerful engine, and lower noise which reduces the environmental impact).

The use of composites in helicopters follows the same objectives (i.e. higher specific strength and stiffness), for parts like main rotor blades, Fig. 10-a, tail rotor blades, composite weapons pylons, Fig. 10-b. The Bell V-280 Valor helicopter, Fig. 10-c, is one of the first military aircraft flying with thermoplastic components, for the reason that thermoplastics can offer advantages in terms of weight, costs, production time, and environmental impact.

(a) – Rotor blade structure

(b) – Black Hawk -60M

(c) – Bell V-280 Valor

(d) – S-97 RAIDER

Fig. 10 – Composites used for helicopters

For both the aircraft structure and the blades carbon-fiber-reinforced composite materials were successfully used. For manufacturing the Bell V-280 Valor helicopter, Fig. 10-c, Bell Helicopter used two thermoplastic composites, induction welded ruddervators, and two compression-molded access panels manufactured from re-used thermoplastic waste material. Ruddervators are the control surfaces for an aircraft with a V-tail configuration; the two compression-molded access panels were manufactured from recycled thermoplastic waste material from the two ruddervator.

The light tactical S-97 RAIDER helicopter, Fig. 10-d, which demonstrated in 2010 to achieve twice the average cruise speed of a conventional helicopter, at more than 463 km/h (250 knots), integrates HexWeb honeycomb core composites and HexPly pre-preg composite technologies, with the ultimate goal to provide the aircraft's structure and blades with reduced weight and extreme strength.

(a) – X-48 B Flying Wing, [5]

(b) – Skyworks Vertijet VTOL

(c) – Transcend Air Vy 400 VTOL

Fig. 11 – Composites used for new concept developments

Taking into account the advantages provided by composites, as reduced weight and

extreme strength, the future prospects of composites are to continuous expansion in use, for the aircraft industry, in large civil aircraft and military aircraft, joined with innovative concept design. Fig. 11 presents significant examples of composite implementation to new concept developments, as X-48 B Flying Wing, Skyworks Vertijet VTOL, Transcend Air Vy 400 VTOL.

Table 1- A summary of military, commercial and general aviation aircraft, incorporating composite materials [7]

Type/ Purpose	Manufactured	Aircraft
Fighter aircraft	U. S., Europe, Russia	AV-8B, F-16, F-14, F/A-18, YF-23, F-22, JSF, Harrier GR.7, JAS 39 Gripen, Mirage 2000, Rafale, Eurofighter, Lavi, MiG-29, Sukhoi Series, UCAV Series
Bomber	U. S.	B-2
Transport	U. S., Europe	KC-135, C-17, B777, B767, MD-11, A320, A340, A380, Tu-204, ATR42, Falcon 900, A300-600
General Aviation		Piaggio, Starship, Premier 1, Boeing 787
Rotary Aircraft		V-22, Eurocopter Series, RAH-66 Comanche, BA609, EH101, Super Lynx 300, S-92

The F/A-18 fighter aircraft, Fig. 12 is a representative example of composites used in military aircraft design.

Fig.12 – Materials used in F/A-18 fighter aircraft, [7]

4. APPLICATION OF COMPOSITES AND TECHNOLOGY ADVANCEMENT TO JET ENGINES FOR LARGE COMMERCIAL AIRCRAFT

Technology advancements in the case of large turbofan engines for commercial aircraft:

1/ increased engine thrust, the enlargement of the fan's blade tip diameter leading to an ingested airflow increase;

2/ application of sweep to fan blades, such that to avoid the occurrence of shock waves at blade tip, while the engine is operated at high rotational speeds; Fig. 13,

3/ expanding the use of composites to fan parts (rotating blades, guide vanes, casings), Fig. 14, allowed the advanced aerodynamic design of fan blades and important decline of weight, and in the same time, as composites provide higher strength and stiffness, allowed product life cycle extension and the diminishing of costs related to manufacturing and maintenance.

Fig. 13 – Technology advances in turbofan engines

Fig. 14 – Fan blade design evolution

The advantages provided by a composite fan blade, Fig. 15, are expressed by the following facts:

1. Titanium leading edge, which ensures ingestion protection, serviceability, replaceability;
2. Polyurethane coating, that brings reduced wear;
3. Composite airfoil, due to higher strength and stiffness, increases the capability to support higher stresses and loads with lowered weight;
4. Low crush stress, does not require lubrication.

Fig. 15 – Composite fan blade (left), fan (right)

Fig. 16 – Composite use on turbofan engine

The use of composites in jet engines, Fig. 16, can be successfully applied for the engine cold parts, like air inlet, fan, and partially to LPC – Low-Pressure Compressor, fuel system, FADEC system, fuel tanks.

Fig.17 – Design and technology advances in jet engines, GE 90 Turbofan Engine, [8]

Key elements of design and technology advances in jet engines are presented in Fig. 17, for the GE 90 Turbofan engine and exemplifying case.

5. SUMMARY OF LESSONS LEARNED ON COMPOSITE USE IN AEROSPACE ENGINEERING

The lessons learned for the primary and secondary composite structures, up to B 787, provided solid information and validations for the implementation of a variety of composite materials, structural design constructions, and fabrication methods. Summarizing the lessons learned, there were used:

- application of advanced composites to aircraft and fiberglass rotor technology;
- carbon fiber epoxy laminates, for all fuselage sections, main wing box, horizontal and vertical stabilizer boxes;
- carbon fiber laminate materials, for the wing leading edge slats and trailing edge flaps;
- carbon sandwich constructions, for secondary structures (rudder, elevators, winglets, nacelle cowlings);
- glass fiber epoxy, other composites, or similar materials, for several fairings on the wing stabilizers, radome, wing-to-fuselage fairings;
- metal alloys, for the leading edge of the nacelles, for the reason of serving as a good heat conductor, for thermal anti-icing;
- titanium-based alloys, for some joints and internal substructures like heavy-load carrying fittings, and for most of the landing gear components;
- advanced composites as fiberglass rotor technology, helicopters/ 2 rotor blade helicopters.

Table 2- A summary composite use in aircraft parts

Aircraft Parts	Composite Materials, Composite Technology
Leading edges	RTM (Resin Transfer Molding)
Clips	TP Stamping
Structural interior parts	RTM, Curing
Thermoplastic rotating parts	Consolidation
Stiffeners	HDF (Hot Drape Forming)
Preforms	HDF
TP consolidated plates	Consolidation
Honeycomb structural parts	Compression&Curing
Turbine blade	Hot forming, Consolidation, RTM

Table 3- A summary composite use in helicopter parts

HelicopterParts	Composite Materials, Composite Technology
Main rotor hub plate	Prepreg curing
Tail rotor blade	RTM (Resin Transfer Molding)
Blade	Prepreg Curing
Structural parts	RTM, Curing

6. APPLICATIONS OF COMPOSITES TO WIND POWER ENGINEERING

According to the vertical or horizontal orientation of the axis, there are VAWT – Vertical Axis Wind Turbine, Fig. 18, and HAWT – Horizontal Axis Wind Turbine, Fig. 20. The use of composites on wind turbine blades (e.g. Vesta V90, Fig. 19 – left) allowed to improve blade bending stiffness and to reduce the mass loads on the blade root, shaft, and tower.

Fig. 18 – VAWT – Vertical Axis Wind Turbine, [11]

Such blades, made of carbon fiber composites (since 2000), are prone to a significantly increased number of load fatigue cycles in comparison with commercial aircraft but are exposed

to similar lightning and hail threats.

Fig. 19 – HAWT – Horizontal Axis Wind Turbine, [11]

7. MANAGEMENT OF ASSUMED RISKS IN CASE OF DAMAGE TOLERANCE

Examples of design load cases and resulting stresses in the case of commercial aircraft are shown in Fig. 20. The damage tolerance concept represents an assumed risk, from the standpoint of the safety management of loads and stresses to which the aircraft is subjected.

Fig. 20 – Aircraft design load cases and resulting stresses, [9].

Fig. 21 – Design load and damage considerations for durability and damage tolerance, [10]

In the case of composites, and especially carbon fiber composites, the “No Crack Growth” Concept of Carbon Fiber Reinforced Polymer (CFRP) is one of the most important Damage Tolerance Requirements. For the aircraft safety operation, health monitoring HM on composite material structures CMS is crucial, (Fig. 21)

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