Composites: materials of the future

Part 10: Composites in aeronautics

Abstract

Naturally derived composites have been used since the early days of aeronautics because of their lightness. Currently, the use of organic matrix composites stems from the constant need to save fuel and particularly fossil fuel. Nevertheless, lightness cannot be obtained at the expense of other properties. On the mechanical level, the relationship between properties and specific weight means that materials can be compared, and this comparison favours composites. Shock resistance (for birds) and electrical properties (for lightning) are other properties which are important for structural materials, in particular polymer-carbon composites.

The use of composite materials is generally accepted for secondary parts (leading edges, flaps, etc.) and it extends to primary structural parts such as the fuselage. Even for motors, manufacturers are now turning to organic matrix composites (including thermoplastics) for parts which are not subject to high temperatures.

The fabrication techniques for composites are generally those requiring pressure and/or high temperatures (compression, (SQ)RTM, ATL, AFP, etc.) for thermosetting resins, and injection for thermoplastics. Nanocomposites and multifunctional hybrid materials open up new possibilities for the future.

History

Since the beginning of aviation, i.e. when engines "heavier than air" started to fly, all manufacturers have sought to reduce the weight of their engines to a minimum.

Clement Ader (1841-1925) is recognized as one of the fathers of aviation (and in fact he invented the word "airplane"). In 1890 he built his first airplane (christened "Eole") which was equipped with a steam engine, a bamboo propeller and mobile canvas wings, and weighed no more than 295kg). Already from the start, aviation was using natural composites.

In 1903, the brothers Orville and Wilbur Wright modified a glider by equipping it with a lightweight car engine. By doing this they made an airplane fly. The airplane was christened "Flyer" and its characteristics are listed in table 1:

Flyer(Orville and Wilbur Wright)	**Characteristics**	
	First flight	17 December 1903
	Engine	1
	Power	12 HP (9kw)
	Wingspan	12.29 m
	Length	6.43 m
	Height	2.74 m
	Surface area of the wings	47.5 m^2
	Empty weight	274 kg
	Maximum weight (with 1 pilot)	338 kg
	Maximum speed	43 km/h

Table 1: Photograph of the Flyer made by the Wright brothers and technical characteristics.

For these first "aircraft", which were based on gliders, minimum weight was always a major concern, especially because of the low power of the engines.

Fuel consumption is also directly related to the weight of the aircraft. The curve in figure 1 shows that, for an airliner at constant speed, fuel consumption is to a close approximation, based on the square of the weight carried.

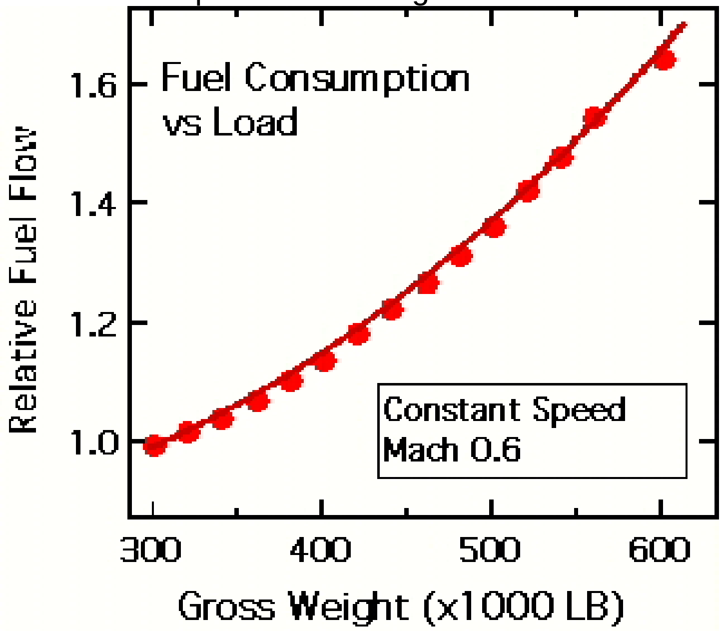
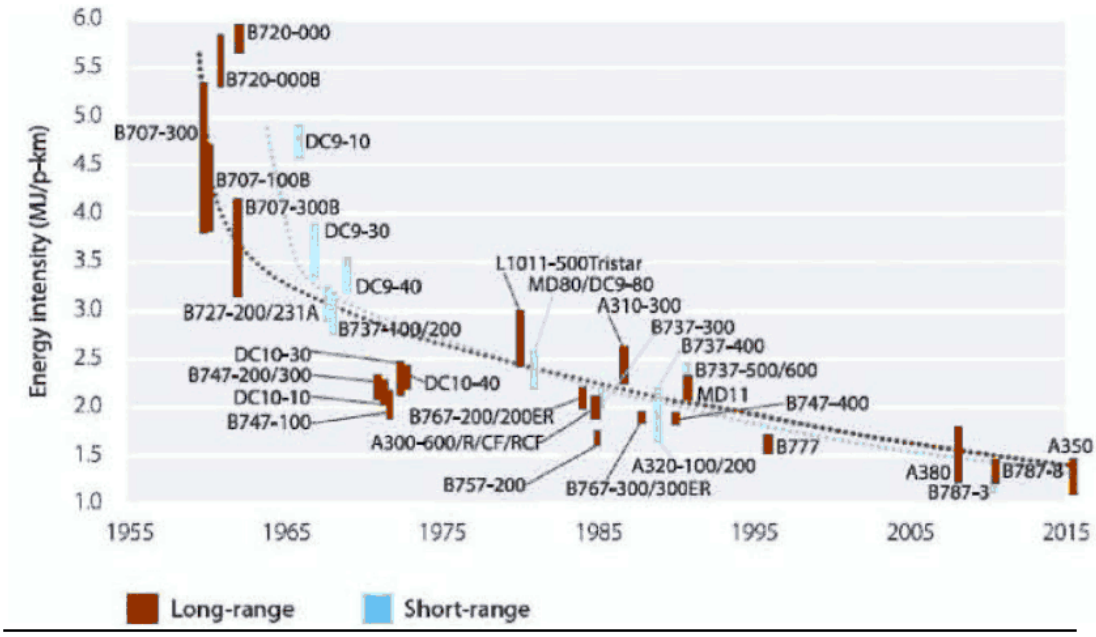


Figure 1: Fuel consumption according to load for a large transport aircraft flying at constant speed.[1]

After a period of "cheap" energy, between 1955 and 1965, the successive oil crises led to aircraft fuel consumption being drastically reduced these days. Figure 2 shows that modern aircraft consume up to four times less energy per passenger and per km than in 1960[2].

[1] http://www.aviation-history.com/theory/lift.htm
[2] http://www.businessinsider.com/high-fuel-costs-help-boeing-and-airbus-2013-7



Source: Lee, IATA

Figure 2: Aircraft energy consumption from 1955 to 2015.

It is interesting to compare the level of composites used in manufacturing the structures of modern equipment (figure 3) and observe the correlation between this level and energy savings.

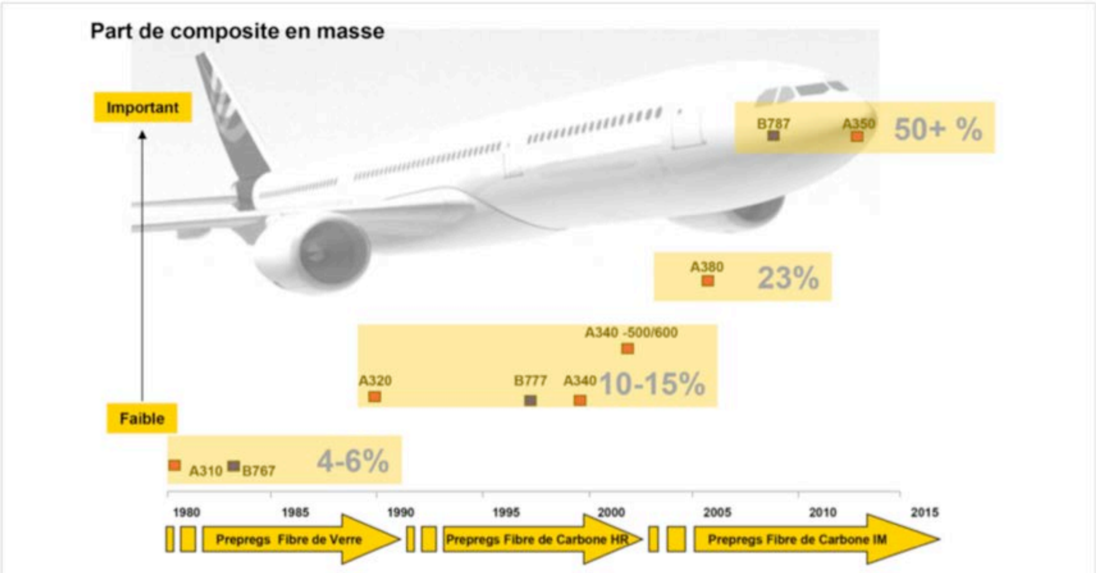


Figure 3: Share of composites in the structure of modern civil aircraft.[3]

To summarise, in aviation even more than in other fields, lightness is an essential parameter to reduce energy consumption, and consequently, to reduce costs and the environmental impact.

Structural materials

The materials used to make aircraft structures must not only be lightweight, but they must be rigid, resistant and resilient (shock-resistant).

[3] http://asso-acit.fr/wp-content/uploads/2013/07/GROUPE_HEXCEL_ACIT_20132.pdf

Table 2 shows however, that generally, the lightest metals are also the least rigid and resistant.

	Specific weight ρ (kg/dm_3)	Stiffness E (GPa)	Resistance σ (MPa)	Specific stiffness (E/ρ)
C (Diamond)	3.5	1000	1050	285
$(CH_2)_n$ Polyethylene	0.95	1	10-50	1.05
Aluminium (Al)	2.7	72	200-550	26.6
Titanium (Ti)	4.5	110	800-1200	24.4
Iron (Fe)	7.8	200	400-1800	25.6

Table 2: Specific weight, stiffness, tensile strength and specific stiffness of structural materials.

Fibre	Ex-PAN[4]			Ex-Pitch[5]	
	Ultra-high strength	High strength	High modulus	Ultra-high modulus	High ductility
Stiffness E (GPa)	291	221	521	940	41
Resistance σ (GPa)	5.69	3.20	3.38	3.21	1.10
Specific stiffness	146	111	261	470	21

Table 3: Stiffness (tensile), tensile strength and specific stiffness of elementary carbon fibres[6] (specific weight: 2 kg/dm^3).

To reconcile mass and stiffness, however, it is advisable to work in specific quantities, that is to say, specific equal mass. This is how the fourth column of table 2 is obtained. It notes that normal metals have a similar specific stiffness, but that carbon (diamond) has a specific stiffness more than ten times greater than that of metals. For sp carbon[2] (carbon fibres made from sheets of graphene) with an orientation in the direction of the C/C connections, the values are also very high as shown in table 3. The best specific stiffness can therefore be expected from materials using oriented carbon. This is the basis of the extensive use of carbon fibre composites in aviation.

The shock resistance (resilience) of structural materials used in aviation is an important parameter. In fact, with the speeds at which modern aircraft fly, the least object can cause sometimes fatal damage (figure 4). The best known example is that of birds which collide with aircraft when they are landing or taking off. The resiliency of epoxy/carbon composites, which much lower than that of metals, is a problem that

[4] Manufactured from polyacrylonitrile (PAN)
[5] Manufactured from pitch
[6] Naito K., Tanaka Y., Yang J.M., Kagawa Y., from: http://www.iccm-central.org/Proceedings/ICCM17proceedings

is currently the subject of research. One solution is to combine the resiliency of thermoplastics with the stiffness and ease of use of thermosetting plastics [7],[8].

Figure 4: Impact of a bird on the wing of a plane with a metal structure.

Other properties, such as the electrical conductivity of structures are more and more important as the proportion of metals, which are good conductors, decreases in structures. Thus the behaviour of aircraft under the impact of lightning is a topical problem with new composite materials which are less conductive (figure 5). Resistance to the impact of lightning while avoiding, as far as possible, excess weight, is an area which requires further research efforts. The current proposed solutions are listed in table 4[9].

Solutions	Aluminium	Copper	Bronze
Wire mesh		X	X
Expanded metal	X	X	X
Sheet metal	X	X	
Metallization	X	X	X

Table 4: Proposed solutions for lightning resistant composites.

[7] PRIFORM® from CYTEC https://www.cytec.com/businesses/aerospace-materials/brands/priform
[8] SKYWIN, "Plan Marshall" project and APC, E-COM, ECOTAC and ICOGEN projects http://www.skywin.be/?q=fr/projets-labellisés
[9] Bréchet Y., cited in: "Aeronautical materials of today and tomorrow". Air and Space Academy, Folder #39 June 2014 (http://www.academie-air-espace.com/publi/newDetail.php?varID=235)

a)

b)

Figure 5: a) distribution of the electrical charge from a lightning bolt on a plane with a metal structure. b) impact of a lightning strike performed in a laboratory on a composite structure[10].

Composite aircraft parts

In modern airliners the proportion of organic matrix composites in structural parts is constantly increasing. The leading edges of the wings, the ailerons and the "flaps" have all been made from composites for a long time already (Fig. 6).

[10] http://blog.dexmet.com/

Figure 6: Rear aileron mount of the Boeing **787 Dreamliner**

Currently, it is the structure of the aircraft itself which is concerned. In the Boeing 787 Dreamliner, the fuselage itself is made largely of composites (Figure 7)
European manufacturers are not far behind and the AIRBUS A350, a competitor of the Boeing 787, has its own fuselage made from composites (Figure 8).

Figure 7: Part of the fuselage of the Boeing 787 Dreamliner

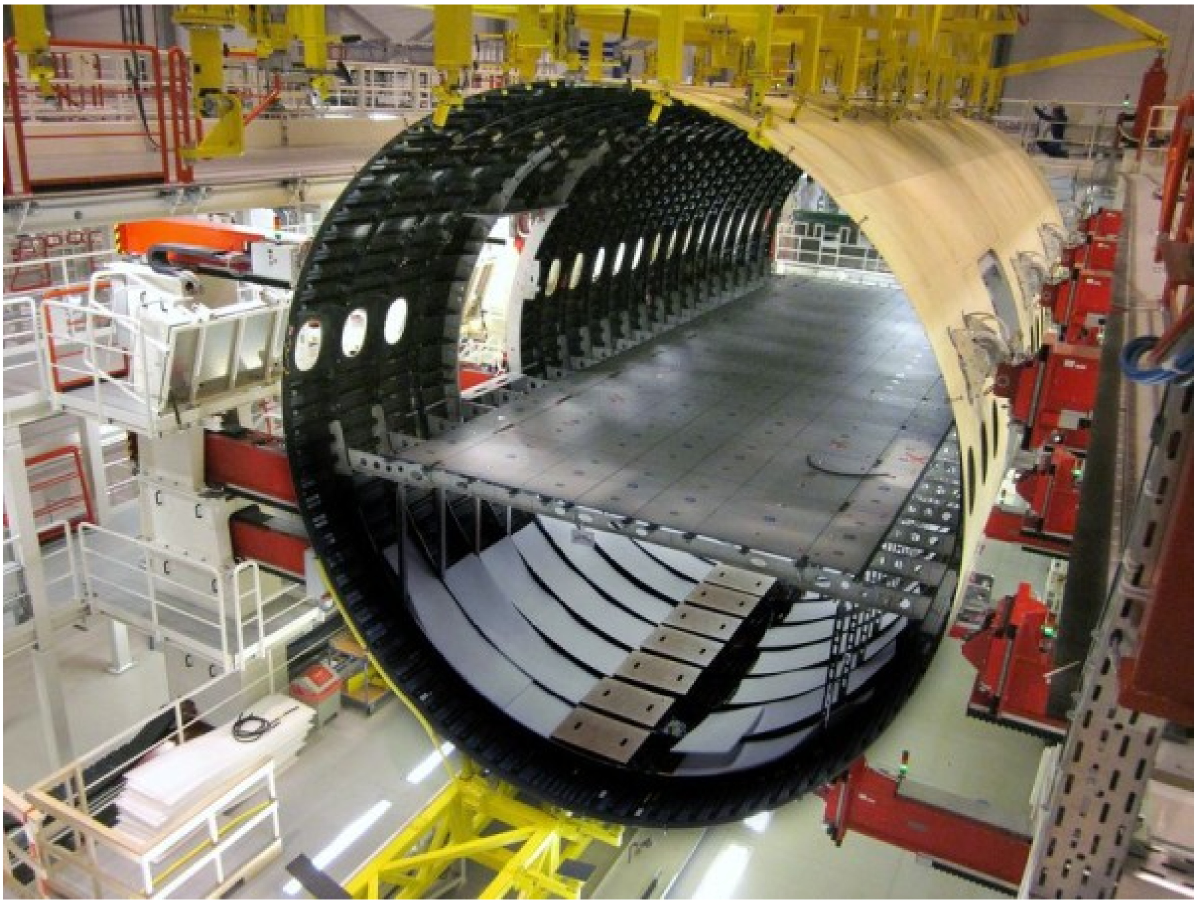


Figure 8: Part of the fuselage of the Airbus A350

While structural parts are increasingly made from organic matrix composites (OMCs), engine parts, which are subject to high temperatures, cannot, for the most part, be made in this type of composite. However, ceramic matrix composites (CMCs) can be used.

Ancillary parts of the engine, such as the low pressure compressors (fig.9), can be made in composites, usually with a thermoplastic matrix.

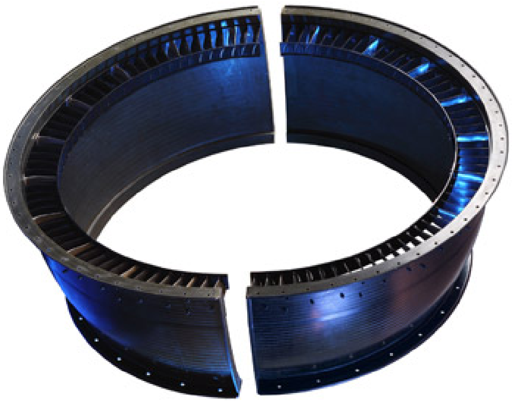


Figure 9: Prototype of a composite diffuser for low pressure compressors (Techspace Aero, Safran Group)[11]

Nevertheless composites are clearly increasingly prevalent in engines as shown in figure 10.

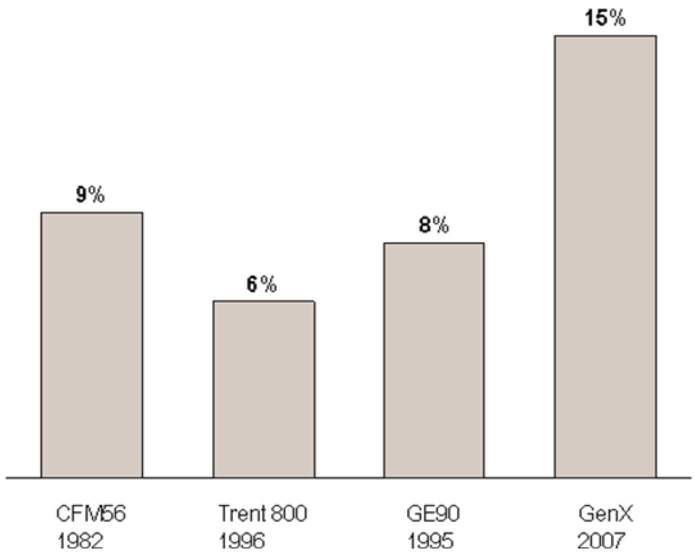


Figure 10: Level of composites in aircraft engines[12]

CFM56: Safran Group: fan blades
Trent 800: Rolls-Royce: fan blades
GE90: General Electric: fan blades
GenX: General Electric: fan blades and hull

Manufacturing techniques

The thermosetting resins used in aeronautics depend on the specifications (mechanical resistance, operating temperature, fire resistance etc.) for each part (figure 11).

[11] http://www.techspace-aero.be/-composites-

[12] Source: Company websites; Industry literature

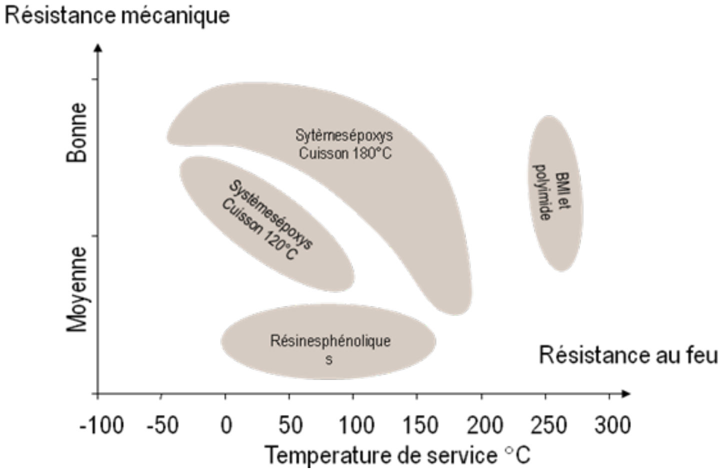


Figure 11: Types of thermosetting resins used in aeronautics[13]

Phenolic resins are used more for the internal parts of aircraft, epoxy resins for secondary structures and increasingly primary structures, and BMI resins are used where temperature resistance is critical in the engine housing.

Moulding techniques (hand layup) cannot be used for large structural parts and they are increasingly being replaced by automated prepreg layup (ATL or Automated Tape Layup) or fibre placement (AFP or Automated Fibre Placement) processes (Fig 12).

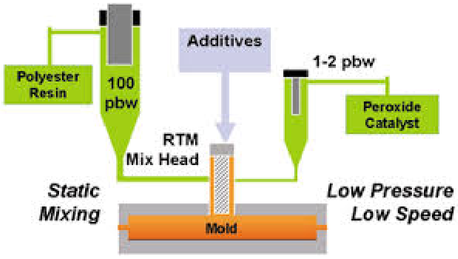
Figure 12: Automated Fibre Placement (AFP) (doc. Sonaca)

Autoclave techniques (fig.13) which are an improved variant of infusion techniques (bag moulding), and mean that parts can be produced with minimum faults, are widely used.

13 Source: Hexcel, press reports, expert interviews

Figure 13: Autoclaves used for aircraft parts (doc. Sonaca)

High pressure injection techniques, such as RTM (Resin Transfer Moulding) (Fig.14) and, more recently, SQRTM[14] (Same Qualified Resin Transfer Moulding), are also widespread.



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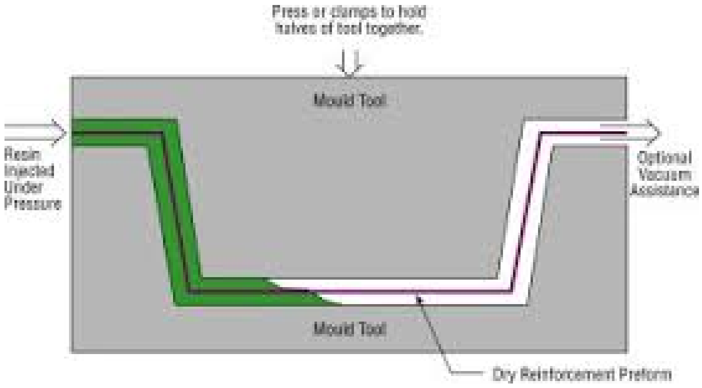

b)

Figure 14: RTM: a) installation diagram b) principle

SQRTM is a recent technique, based on RTM but injecting the same resin as that used for prepregs, which means that an additional qualification stage can be avoided. This qualification process is a detailed (and therefore long) procedure which is intended to control the properties of the materials and the processes used for the primary and secondary aircraft structures[15].

[14] http://en.wikipedia.org/wiki/Out_of_autoclave_composite_manufacturing

[15]: Report from the Federal Aviation Administration. William J. Hughes Technical Centre's Full-Text Technical Reports: http://www.faa.gov/about/office_org/headquarters_offices/ang/offices/tc/library/

Outlook

The aerospace composite materials sector is still undergoing significant development, particularly with the introduction of nanocomposites, hybrid materials and aerogels, etc.[16]

[16] Meador, M., A., NASA, Polymeric Materials for Aerospace Power and Propulsion- NASA Glenn Overview