COMPOSITE MATERIALS USAGE IN AIRCRAFT STRUCTURES

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This article contains information about the aerospace composite industry. Inform about the representation of composite materials in aircraft structures over the past half-century. It describes the advantages provided by composite materials (CFRP mostly) for aircraft structure. It shows their actual usage in aircraft design. It describes the modern production process air components for large transport aircraft. At the end is mentioned strict commitment to reduce emission of CO_2, which has set the Advisory Council for Aeronautical Research in Central Europe.

K e y w o r d s: composite, material, carbon, epoxy, pre-preg, CFPR, aircraft, structure, manufacturing

1 INTRODUCTION

Aerospace engineering is changing. Aeroplanes have traditionally been made out of metal – usually alloys of aluminium; now however, engineers are increasingly working with carbon fibre composites. Fibrous composite materials were originally used in small quantities in military aircraft in the 1960s, and within civil aviation from the 1970s. By the 1980s (Fig. 1), 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. However, it is with the advent of the latest generation of airliners, such as the Airbus A380 (Fig. 2) , the world's largest passenger aircraft, that these materials have been deployed extensively in primary loadcarrying structure. The A380 uses composite materials in its wings, which helps enable a 17% lower fuel use per passenger than comparable aircraft.

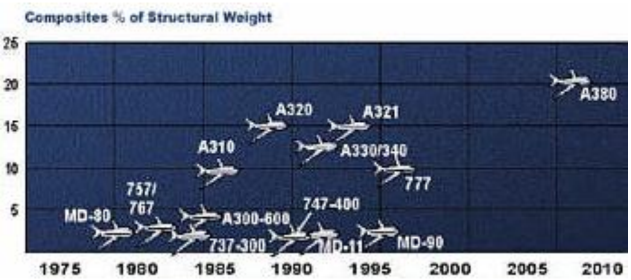

Fig. 1 Composite applications in commercial aircraft

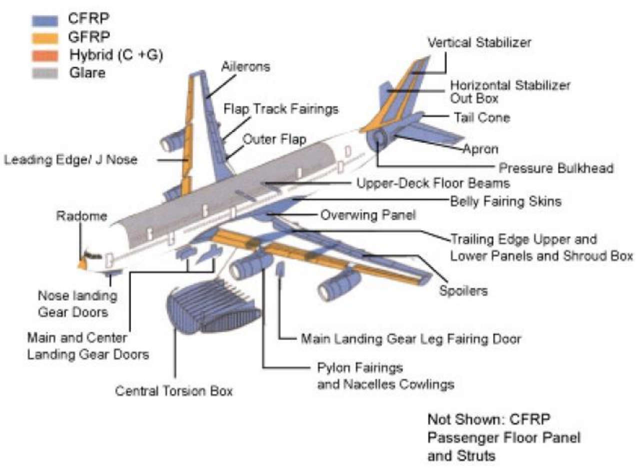

Fig. 2 Airbus A380

2 COMPOSITE MATERIALS

Composite materials (for aerospace uses, this is usually a carbon/epoxy mix) can provide a much better strength-to-weight ratio than metals: sometimes by as much as 20% better. The lower weight results in lower fuel consumption and emissions and, because plastic structures need fewer riveted joints, enhanced aerodynamic efficiencies and lower manufacturing costs.

The aviation industry was, naturally, attracted by such benefits when composites first made an appearance, but it was the manufacturers of military aircraft who initially seized the opportunity to exploit their use to improve the speed and manoeuvrability of their products. Civil aircraft manufacturers have been slower to implement them in their airframes for two reasons: stringent civil airworthiness requirements deterred the wholesale adoption of relatively unproven materials and the flat price of fuel in the late 1980s reduced the need for increased fuel efficiency in emerging airliner designs.

Now, however, with extensive experience in the use of composites within the industry, and against the backdrop of European-wide targets to reduce emissions from aircraft, the value of realising the full potential of this important technology is clear.

Carbon fibre reinforced plastic (CFRP) – carbon fibres embedded in an epoxy matrix (Fig. 3) – derives its high structural performance from the prodigious strength of the individual strands of carbon.

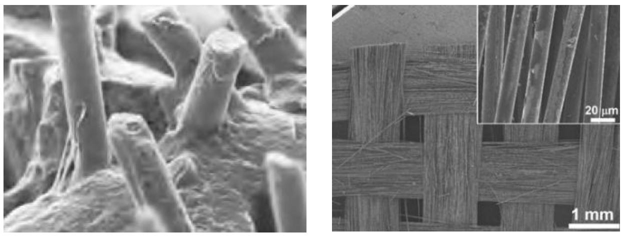

Fig. 3 Microscope photo: interface fibre – matrix and plain weave fabric

By way of comparison, the ultimate strength of aerospace grade aluminium alloys is typically 450 megapascals (MPa), whilst that of a carbon fibre would be five times that value (approx. 2200 MPa and more). As carbon composites are, additionally, only 60% of the density of aluminium, the potential for weight reduction in an airframe application is also apparent. Glass, aramid and boron fibres are also used, but for primary load-bearing structure, carbon fibres have the best combination of strength and cost. In addition to strength and weight, fibrous composites are thought to be virtually **immune from 'fatigue'**. Relatively small cracks in metal continue to grow, and it was this phenomenon of progressive cracking that saw the demise of the first de Havilland Comet design during the early jet age in the 1950s. However, because of the structure of composites – they are non-homogeneous – cracks will not be able to spread. This means that structural engineers can perform design and analysis assuming much higher resistance to stress, and concern themselves less with the long term durability of the structures they design.

The composite material systems which have been considered usefulin aerospace sector are based on reinforcing fibres and matrix resins given in tables 1 and 2, respectively. Most aerospace composites use prepregs as raw materials with autoclave moulding as a popular fabrication process.

Table 1. Reinforcing fibres commonly used in aerospace applications.

Fibre	Density (g/cc)	Modulus (GPa)	Strength (GPa)	Application areas
Glass				
E-glass	2·55	65–75	2·2–2·6	Small passenger a/c parts, aircraft interiors, secondary parts; Radomes; rocket motor casings
S-glass	2·47	85–95	4·4–4·8	Highly loaded parts in small passenger a/c
Aramid				
Low modulus	1·44	80–85	2·7–2·8	Fairings; non-load bearing parts
Intermediate modulus	1·44	120–128	2·7–2·8	Radomes, some structural parts; rocket motor casings
High modulus	1·48	160–170	2·3–2·4	Highly loaded parts
Carbon				
Standard modulus (high strength)	1·77–1·80	220–240	3·0–3·5	Widely used for almost all types of parts in a/c, satellites, antenna dishes, missiles, etc
Intermediate modulus	1·77–1·81	270–300	5·4–5·7	Primary structural parts in high performance fighters
High modulus	1·77–1·80	390–450	2·8–3·0 4·0–4·5	Space structures, control surfaces in a/c
Ultra-high strength	1·80–1·82	290–310	7·0–7·5	Primary structural parts in high performance fighters, spacecraft

3 AIRFRAME USAGE

3.1 Airframe usage

In order to derive maximum benefit from the use of carbon composites, it is essential to direct the fibres in the direction of the main stress. For example, the wing of an aircraft bends during take-off, landing and flight, meaning that it is subject to stress across its span. To support this, engineers orient up to 60% of the fibres along the wing skins and the span-wise internal stiffeners. In addition, wing skins are subject to parallel stresses known as shear stresses – to combat this, plies are directed at 45°. Components inside the wing, such as spars and ribs that are designed to bear shear stresses, are made of up to 80% of 45° plies (Fig.4).

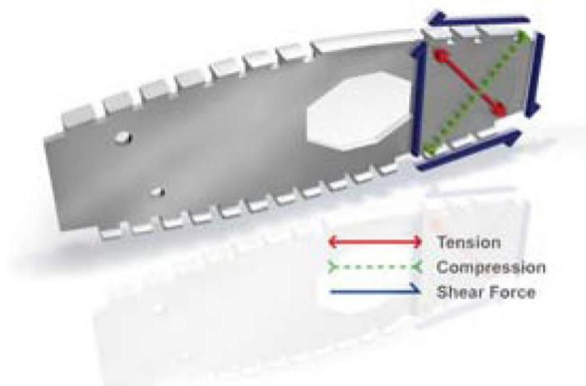

Fig. 4 Schematic schowing shear forces on the spar

Table 2. Polymeric matrices commonly used in aerospace

Thermosets				Thermoplastics
Forms cross-linked networks in polymerization curing by heating				No chemical change
Epoxies	Phenolics	Polyester	Polyimides	PPS, PEEK
• Most popular • 80% of total composite usage • Moderately high temp. • Comparatively expensive	• Cheaper • Lower viscosity • Easy to use • High temp usage • Difficult to get good quality composites	• Cheap • Easy to use • Popular for general applications at room temp	• High temp application 300°C • Difficult to process • Brittle	• Good damage tolerance • Difficult to process as high temp 300–400°C is required
• Low shrinkage (2–3%); • No release of volatile during curing	• More shrinkage • Release of volatile during curing	• High shrinkage (7–8%)		
• Can be polymerized in several ways giving varieties of structures, morphology and wide range of properties	• Inherent stability for thermal oxidation. • Good fire and flame retardance • Brittle than epoxies	• Good chemical resistance • Wide range of properties but lower than epoxies. • Brittle • Low T_g		
• Good storage stability to make prepregs	• Less storage stability-difficult to prepreg	• Difficult to prepreg		• Infinite storage life. But difficult to prepreg
• Absolute moisture (5–6%) causing swelling and degradation of high temp properties • Also ultra violet degradation in long term	• Absorbs moisture but no significant effect of moisture in working service range	• Less sensitive to moisture than epoxies		• No moisture absorption
• Density (g/cm^3) 1·1–1·4	• Density (g/cm^3) 1·2–1·4	• Density (g/cm^3) 1·1–1·4		• Density (g/cm^3) 1·3–1·4
• Tensile modulus 2·7–5·5 GPa	• Tensile modulus 2·7–4·1 GPa	• Tensile modulus 1·3–4·1 GPa		• Tensile modulus 3·5–4·4 GPa
• Tensile strength 40–85 MPa	• Tensile strength 35–60 MPa	• Tensile strength 40–85 MPa		• Tensile strength 100 MPa

In this way, the direction at which the plies are laid ensures that material volume, and hence weight, is kept to a minimum consistent with adequate strength. In terms of the impact on the work of structural engineers, that caused by the advent of CFRP has been considerable – they can now effectively choose the stiffness characteristics of the material they are using. Taking this a step further, engineers are also collaborating with aerodynamicists to explore 'aeroelastic tailoring'. Aircraft wings are designed in the knowledge that their shape impacts on their lift and load distribution, but also that lift and load distribution will alter their shape. By employing aero-elastic tailoring, structures engineers can generate wing designs that deflect under increases in loading in such a way as to moderate the internal load increase. CFRP is peculiarly amenable to this type of design because, by orienting fibres in specific directions, the stiffness characteristics of a laminate can be modified to give precisely the response to increased load that is required.

4.2 Usage in modern aircraft

Following the Airbus lead with its A380, a number of current large aircraft development programmes are looking to use composites more extensively within the wings and fuselage. The Boeing 787 'Dreamliner', for example, is made approximately of **50%** composite materials (Fig. 5).

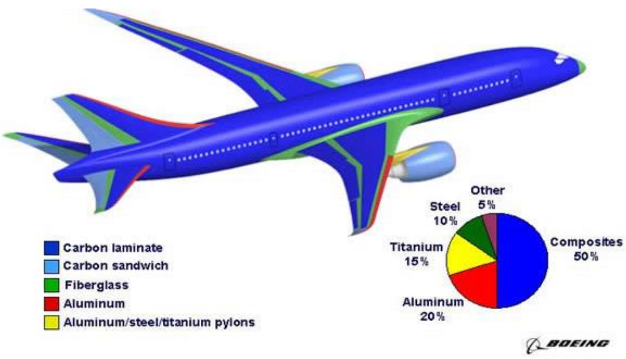

Fig. 5 Composite solution applied throughout the Boeing 787

This revolutionary aircraft uses a novel process of ‘winding’ composite layers, like the winding of a cotton reel, in the fabrication of large, joint-less, fuselage sections. Meanwhile the Airbus A400M, the next generation of military airlifter, similarly has wings made from carbon fibre composites. This aircraft is designed to withstand the severe loads associated with operations from informal landing strips like deserts and fields, and it benefits from the superior fatigue resistance of carbon composites. The design intent is that A400M aircraft will spend less time in the maintenance hanger and more time flying missions. The Airbus A350 is made of **52%** composite materials (Fig. 6).

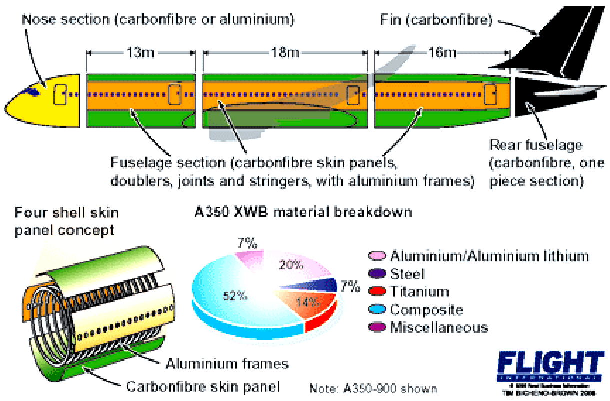

Fig. 6 Airbus A 350 XWB structural design

Beyond these aircraft, the indications are that the next generation of single-aisle airliners, ubiquitous throughout the world fleet in making 1,000-3,000 nautical mile flights with payloads of 100-180 passengers, will employ carbon composites extensively in their airframe structure.

4 MANUFACTURING COMPOSITES

When applied to aircraft structures, carbon composites are generally supplied in unidirectional (UD) form: thin (apr. 0.125 – 0.25 mm thick) sheets or tapes of parallel fibres that have been pre-impregnated with resin that has yet to set. This form of the material is ideal for the manufacture of thin plates that are used so extensively in airframe structures. Manufacturers use tapelaying machines (Fig. 7) to lay down layers, or plies, of this material, one on top of the other, to form single piece sub-components.

By laying successive plies in different directions, the strength and stiffness of the component can be tailored to match the demands of the engineer, allowing adequate structural properties to be attained for minimum weight. Modern tape-laying machines can fabricate an entire wing skin in one piece, eliminating the fasteners that are routinely used in metallic designs and thus saving manufacturing cost and further reducing overall weight. To complete the manufacturing process, the component is cured within an autoclave, which subjects the component to pressure at an elevated temperature to consolidate and harden the layers of plies into a single monolith of carbon/epoxy laminate.

Carbon/epoxy composites for aerospace use are generally fabricated in a laminated form. The epoxy resin requires ‘curing‘ (hardening) through the application of heat, whilst the stack of plies that forms the laminate requires consolidation to avoid the formation of inter-lamina spaces or “voids”. Pressure is applied to the laminate to achieve consolidation.

Fig. 7 Tapelaying machines for Airbus wings

Pre-preg material is supplied in rolls or tape, and comprises fibres in woven or UD form pre-impregnated with uncured epoxy resin. The material is usually stored in refrigerators to prevent premature curing of the resin at room temperature. The material is cut and laid-up in a tool (mould) by machine, but must then be vacuumbagged by hand prior to the curing process. The cure takes place in an autoclave (Fig. 8) – a pressurised oven – that subjects the embryonic component to the pressure required to ensure consolidation and the temperature necessary to achieve hardening of the epoxy. Manufacturing and production engineers are searching for ways of reducing the costs and times to produce composite components.

Fig. 8 Autoclave for wings and other large composites components

Pre-preg materials are generally more expensive, both to buy and to store, than are the component parts (carbon fibre and epoxy resin) singly. Autoclaves are expensive pieces of equipment, and their presence increases the floor space occupied by a factory equipped for pre-preg production. For these reasons alternative forms of the raw materials and manufacturing processes are being sought. Typical composite material systems in aerospace sector is show in table 3.

Engineers are directing increasing interest at the use of "non-crimp" fabric (NCF). NCF is dry carbon fibre material, which is cheaper than pre-preg. However, the absence of resin leaves the fibres free to separate from one another, making the material impossible to store or to work with. To hold the dry fibres together they are lightly stitched to form the fibres into a fabric that holds together and makes it workable, yet retains the strength and stiffness advantages of UD pre-preg.

Table 3. Typical composite material systems in aerospace

Material system	Application area
♦ 175°C curing high strength-carbon-epoxy – Zero-bleed (neat resin content) UD prepregs – 5HS or 8HS bi-directional fabric prepreg – toughness, good out-life and shelf-life	Structural components of fighter aircraft and helicopters. e.g. wing skins, spars, fin, rudder, elevons, doors, etc.
♦ 175°C curing intermediate modulus carbon with epoxy + BMI/cynate-ester – Zero-bleed (neat resin content) UD prepregs – 5HS or 8HS bi-directional fabric prepreg – high toughness, good out-life and shelf-life – low environmental degradation	Frames, stiffeners, rotor blades
♦ 120°C curing HS-carbon-epoxy – Zero-bleed (neat resin content) UD prepregs – 5HS or 8HS bi-directional fabric prepreg – toughness, good out-life and shelf-life	Structural components of helicopters or transport aircraft. e.g. spars, fin, rudder, elevons, doors, etc. Frames, stiffeners
• Aramid fibre in low-loss polyester/cynate esters	Radome
• Cu-mesh epoxy prepreg	For Lightning Strike protection Wing-skin, others
♦ E-glass fabric in epoxy resins – High temp curing – RT/moderate temp curing	Fighters fairings, fin-radome, drop-tanks Small transport aircraft structural components : : Fuselage, wing, other

In terms of the manufacturing process there is an on-going research effort throughout the industry to eliminate autoclaves. The heated mould tool is one means of achieving the elevated temperature necessary to cure the resin without the use of a separate oven, but this approach still leaves the issue of laminate consolidation unresolved. Vacuum bagging allows a pressure of up to one atmosphere to be applied to the laminate, although this falls short of what can be achieved in an autoclave. For this reason the geometries of component that can utilise this production approach may be restricted. Hopefully the money that is being invested in research in this area will enable such technology to be used in an increasing range of aerospace components.

Manufacturing engineers are, similarly, wrestling with unfamiliar difficulties. Problems with wrinkling of the fibres in the fabrication process, resulting in a loss of stiffness and strength in the finished component, are addressed only by imposing strict constraints on the geometry of structural features. The spectre of void formation in the resin matrix caused by a lack of consolidation of the plies during the curing process – reminiscent of Swiss cheese – creates further geometric constraints. As a consequence, engineers working with composites have realised that designing with manufacture specifically in mind is equally as important as designing for the strength/weight ratio.

These issues are a small selection from a list that includes topics as diverse as the drilling of holes in the assembly of mixed composite/metallic components to the provision of electrical diverter strips to satisfy lightning strike requirements for the finished airframe. So, the widespread introduction of CFRP must be implemented in an intelligent way.

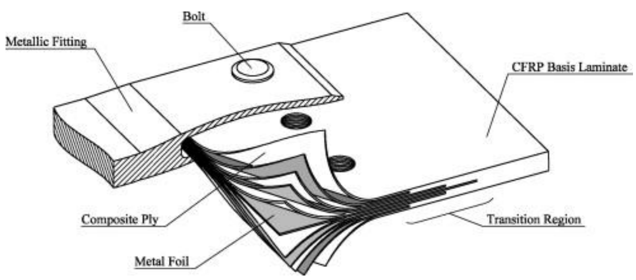

Fig. 9 Local hybridization at the titanium bolted joint location

5 CONCLUSION

The environmental case for developing our understanding and increasing our exploitation of composites is compelling. The Stern Review, 2006, identified that 1.6% of global greenhouse gas emissions come from aviation but that the demand for air travel will rise with our income. To combat the environmental threat that aviation poses, the Advisory Council for Aeronautical Research in Europe in 2002 laid out targets to reduce the emission of CO_2 (an important greenhouse gas) from an aircraft by 50% by 2020.

The reduction of airframe weight through the extensive use of carbon composites is just one of a range of technologies that must be deployed to meet such a challenging target. To meet the challenge that the widespread use of composite materials throws up, the civil aerospace community has launched the Next Generation Composite Wing (NGCW) research programme. The environmental obstacle that confronts the aviation industry is, perhaps, the greatest it has faced in its 100 year history, the adoption of CFRP being one facet of the industry's plan to surmount it.

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