

COMPOSITE MATERIALS REVOLUTIONISE AEROSPACE ENGINEERING

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. Tim Edwards, a structural engineer at Atkins, describes the making of composite wings and the take-up of them across the aerospace industry.

Airbus A400M, the next generation of military airlifter expected to make its first flight later this year, has wings made from carbon fibre composite. By using composites rather than metals the overall strength to weight ratio of materials used in aircraft design can improve by up to 20% © Airbus Military



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, 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, the world's largest passenger aircraft, that these materials have been deployed extensively in primary load-carrying structure. The A380 uses composite materials in its wings, which helps enable a 17% lower fuel use per passenger than comparable aircraft.

LIGHTER, STRONGER

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.

FATIGUE FREE

Carbon fibre reinforced plastic (CFRP) – carbon fibres embedded in an epoxy matrix – derives its high structural performance from the prodigious strength of the individual strands of carbon. By way of comparison, the ultimate strength of aerospace grade aluminium alloys is typically 450 megapascals (MPa – a unit of stress or pressure, one MPa being about 10 times atmospheric pressure), whilst that of a carbon fibre would be five times that value. 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

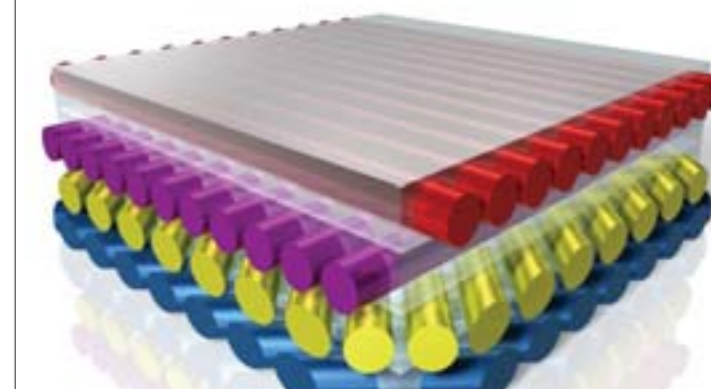
means that structural engineers can perform design and analysis assuming much higher resistance to stress, and concern themselves less with the long term durability of the structures they design.

MANUFACTURING COMPOSITES

When applied to aircraft structures, carbon composites are generally supplied in uni-directional (UD) form: thin (~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

COMPOSITE MATERIALS AT A GLANCE

- Composites are essentially plastics reinforced with carbon fibres.
- Carbon fibres, each no larger than a human hair, are set into resin to form sheets, or plies.
- Plies are laid on top of each other to form sub-components.
- The strength and stiffness of the materials depends on the direction at which the plies have been laid together.



of thin plates that are used so extensively in airframe structures.

Manufacturers use tape-laying machines 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.

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. 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 ‘aero-elastic 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.

THE DESIGN CHALLENGES

The foregoing description of carbon composites might lead one to question whether all of this is too good to be true: surely this wonder material must have some Achilles’ heel?

Indeed, there are several obstacles to achieving the low weight and low cost that the headline figures promise. Engineers are overcoming the difficulties progressively through improved design and novel manufacturing processes, but the current state of development sees engineers of all disciplines searching for the best answers.

Structural engineers are faced with worries regarding damage tolerance and delamination, but they must also contend with the less forgiving

nature of the new materials when compared with metals.

Metals have the desirable quality that they exhibit plasticity: under high loads they undergo permanent deformation (ie they bend or stretch) before they break. As a result, a metallic structure can absorb everyday small impacts (leading to dents) with very little reduction in its basic strength. Plasticity allows loads

in highly stressed regions to be re-distributed to regions of lower stress, ensuring that any stress concentrations inherent in a design do not lead to premature structural failure.

Carbon/epoxy composites, by contrast, exhibit little or no plasticity. Consequently, small in-service impacts tend to create local breakdowns of the epoxy matrix, leading to a weakening of the laminate in the area of

the impact. In addition, stress concentrations in a composite design can cause sudden structural failure at high load; the process would be incremental with a similar design in metal because the load would be redistributed.

Structural engineers combat this lack of damage tolerance by assuming much lower stress values than theoretically necessary when they are designing, and they have had to accept an increase in the complexity of their strength calculations to accommodate the greater sensitivity of CFRP at high loads.

MANUFACTURING CHALLENGES

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

MANUFACTURING PROCESSES

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.

The predominant manufacturing approach for aerospace structures employs ‘pre-preg’. 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 vacuum-bagged by hand prior to the curing process. The cure takes place in an autoclave – 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. 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.

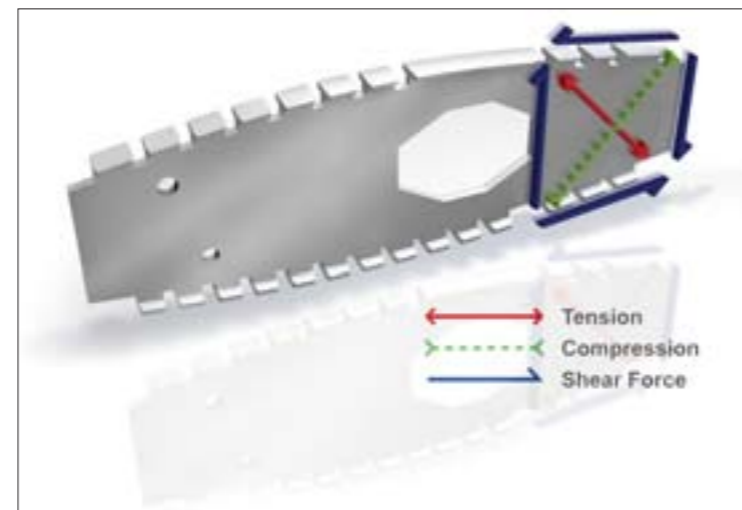
Engineers are directing increasing interest at the use of ‘non-crimp’ fabric (NCF). NCF is dry carbon fibre material, which is cheaper than pre-preg. However, the absence of resin leaves the fibres free to separate from one another, making the material impossible to store or to work with. To hold the 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.

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.



Schematic showing the ribs within a wing



Schematic showing shear forces on the spar



An engineer inspects the spar for de-laminations using an ultra-sonic probe © GKN Aerospace

NEXT GENERATION COMPOSITE WING (NGCW) RESEARCH PROGRAMME

The project was launched in May 2008 and has over £103 million of funding allocated to it by its various industry partners, and the Government's Technology Strategy Board, Regional Development Agencies and Devolved Administrations.

This investment will enable engineers to develop wing box performance analysis tools that will give a better

understanding of how they can use composite materials to best advantage in the wing. By developing standard tools that can be used to test the potential performance of composites, engineers also hope to open the doorway to the increased use of composites in other industries.

The areas of research that will be undertaken in this programme focus, naturally, on the use of CFRP in civil aircraft wing structures, but the studies also encompass the interaction of the structure with the aircraft system as a whole. Aero-elastic

tailoring is one example of such interaction. Another example relates to the fuel system. The wing is generally employed to carry fuel, and carbon composite wing structures can be more susceptible to damage from high fuel pressures than metallic counterparts due to the possibility of de-lamination. Thus, design of the fuel system to moderate maximum fuel pressures allows a reduction in the weight of a composite wing structure.

Atkins is a core partner in the NGCW programme,

with a particular focus on optimising composite wing design. This will include exploring unconventional lay-ups of the carbon fibres to see how stiffness, strength, and resistance to buckling can be maximised. At the same time, detailed consideration will be given to the manufacturing techniques employed so that laminate lay-up times can be minimised, and the final assembly process optimised to maximise production rate for the next generation of commercial transport.

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.

APPLICATIONS

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, may eventually be made of as much as 50% composite materials. 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 expected to make its first flight later this year, 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.

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.

FUTURE USES

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 CO₂ (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 in the UK has launched the Next

Generation Composite Wing (NGCW) research programme, which seeks to answer some of the questions – see panel above.

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. The NGCW programme should see the UK aerospace industry well placed to be in the vanguard of the intelligent application of these very promising materials.

BIOGRAPHY – Tim Edwards

Tim Edwards is Chief Structural Engineer in the Aerospace division of the engineering consultancy Atkins. The company's Aerospace division works with clients, including Airbus and Rolls-Royce, on the design and analysis of aircraft structures and aero engines. His composite experience includes work on the carbon composite outer wing box spars for the Airbus A400M, certification of the Airbus A380 and, more recently, research work under the Next Generation Composite Wing programme. He completed an undergraduate apprenticeship with British Aerospace and graduated in aeronautical engineering from Imperial College.