Composites methods development under the next generation composite wing (NGCW) research programme

032

Tim Edwards

Chief Structural Engineer
Defence, Aerospace and Communications
Atkins
Bristol, UK

Abstract

The Next Generation Composite Wing (NGCW) project was launched at an event at the Institution of Civil Engineers, London 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. The project is led by Airbus in the UK, with Atkins, as one of the industry partners, committing the efforts of three full-time engineers over a period of three years.

1. Introduction to the NGCW Programme

The project is part of Airbus' response to the ACARE (Advisory Council for Aeronautical Research in Europe) 2020 targets for a halving of civil aircraft CO2 emissions by that year relative to the standards of 2000. The introduction of carbon fibre reinforced plastic (CFRP) materials into the primary structure of the wing box is seen as a vital component of this response, as composites offer the potential for significantly reduced airframe weight when compared with more traditional aluminium alloys. The NGCW investment will enable aerospace engineers to develop techniques and tools that will give a better understanding of how they can use composite materials to best advantage in the wing of a civil transport. By developing standard analysis tools, our engineers also hope to open the doorway to the increased use of composites in other industries.

The NGCW project is divided into four components that focus on critical aspects of wing design and manufacture. The multi-disciplinary optimised wing (MDOW) component is the one on which Atkins has focussed its efforts, this package having the aim of producing a wing structure that is optimised to account for all aspects of wing design: weight, aerodynamics and systems integration. The remainder of the NGCW programme comprises HiVol (high volume production), which seeks to minimise the manufacture and assembly costs of composite wings, IntEq (integrated equipment), which examines the optimisation of fuel, hydraulic and electrical systems within the

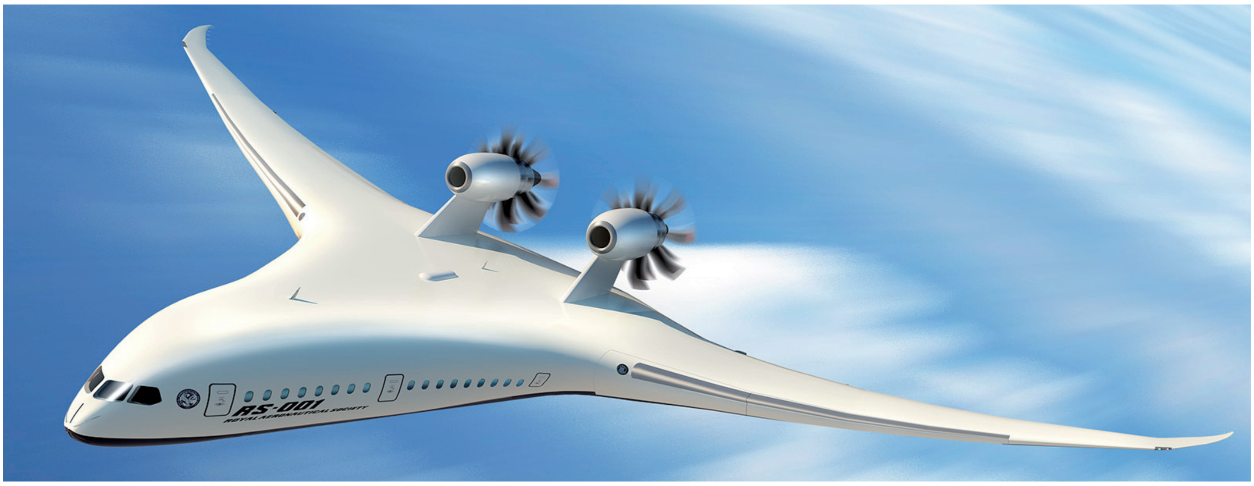

FIGURE 1. A CONCEPT FOR A FUTURE GENERATION CIVIL AIRCRAFT
(DIGITAL IMAGE BY KAKTUS DIGITAL (WWW.KAKTUSDIGITAL.COM) FROM ORIGINAL CONCEPT BY RAES

wing, and MINT (multi-disciplinary integration), which integrates the output from the other three studies into an analysis system that will deliver a highly efficient and cost-effective CFRP wing within the ACARE time scales.

2. Carbon fibre reinforced materials

CFRP combines high strength carbon fibres embedded in an epoxy matrix. When applied to aircraft structures, carbon composites are generally deployed as laminates: a stack of plies, or laminas, each ~0.125 – 0.25mm thick. A ply is supplied in uni-directional (UD) form: a sheet or tape of parallel fibres that has been pre-impregnated with resin that has yet to be cured. This form of the material is ideal for the manufacture of thin plates that are used so extensively in airframe structures. Manufacturers use tape-laying machines to lay down plies, one on top of another, to form single piece sub-components. 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 time and cost, and component 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.

It is the fibres that give composite materials their potentially decisive strength advantages. By way of comparison for static strength, the ultimate strength of aerospace grade aluminium alloys is typically 450 megapascals, whilst that of a carbon fibre would be five times that value. In addition, fibrous composites are virtually immune from fatigue under in-plane loading, as the fibres arrest the growth of local defects before they can propagate. Again, aluminium alloys exhibit no endurance limit, so fatigue in metallic structures is an ever-present threat. As carbon composites are, additionally, only 60% of the density of aluminium, the potential for weight reduction in an airframe application is obvious.

To obtain the required multi-axial stiffness and strength within the structure, successive UD plies are orientated at a variety of angles – normally at angular increments of 45°. By judicious choice of angular distribution, the stiffness and strength of the final laminate may be chosen to match the demands of the local structure. For example, if high direct stiffness/strength is required in the 0° direction, some shear capability also (+/-45° direction), but not very much in the 90° direction, a lay-up of 50% 0s, 40% +/- 45s and 10% 90s might be selected (50/40/10).

Thus, carbon composites provide engineers with a means of reducing both manufacturing cost and structure weight. Clearly, however, the additional design freedoms extended to the engineers bring with them a more onerous analysis task, so that the optimal use of the material is more complex than in the case of metallic design.

3. Atkins' commitment to NGCW

Atkins is a core partner in the MDOW component of the NGCW programme, and has targeted two aspects of that study as its key contributions: investigation of the performance of novel laminates; and the rapid sizing of composite wing box components. These two technologies are aimed at the heart of optimised CFRP wing structures: how can the fibres best be deployed within a structure, and how can structural analysis be accelerated to allow investigation of the increased variety of structural options that the use of CFRP presents?

In terms of novel laminates, the Atkins work to date has concentrated on aspects of fibre angle, the distribution of ply angles, and a variety of aspects of inter-lamina strength (inter-lamina strength is a key weakness in composite materials). Rapid sizing techniques have concentrated on improving the idealisations applied to the analysis of wing box components and the introduction of composite integrity assessment techniques so that accurate sizes may be derived without the need to resort to time-consuming finite element analysis.

The target from the MDOW developments is the implementation of a process that will allow a complete sizing iteration for a wing configuration to be performed in less than 24 hours. Rapid sizing iteration is seen as a fundamental requirement of the goal of simultaneous multi-disciplinary optimisation that was a key message in the ACARE report of 2002.

4. Ply angle study

Traditionally, laminated composite materials have deployed UD plies in stacks with four associated orientation angles: 0°, +45°, -45° and 90°. These orientations are selected to generate high strength and stiffness under direct loading in the principal (0° and 90°) directions, whilst simultaneously maintaining mechanical properties under shear loading (+45° and -45° directions). Typical composite wing box skin (top and bottom aerodynamic surfaces) laminates, for example, comprise plies orientated in these 0°/+-45o/90° directions in the proportions 50%/40%/10%.

It is generally true that the chord-wise stiffness (Ey) and strength of the skins is of small significance. Much more important is the span-wise stiffness (Ex)/strength and the shear stiffness (Gxy)/strength, since the principal loads in the wing box (see Figure 2) comprise bending and torsion. Atkins has been studying the effects of narrowing the angle of the "angle plies" – those oriented at +45° and -45°. The potential benefit of such a revision is illustrated in Figure 3. Reduction of the 45° angle promises a significant increase in span-wise stiffness and strength, whilst having a negligible impact on shear performance.

The studies by Atkins have concentrated on laminate

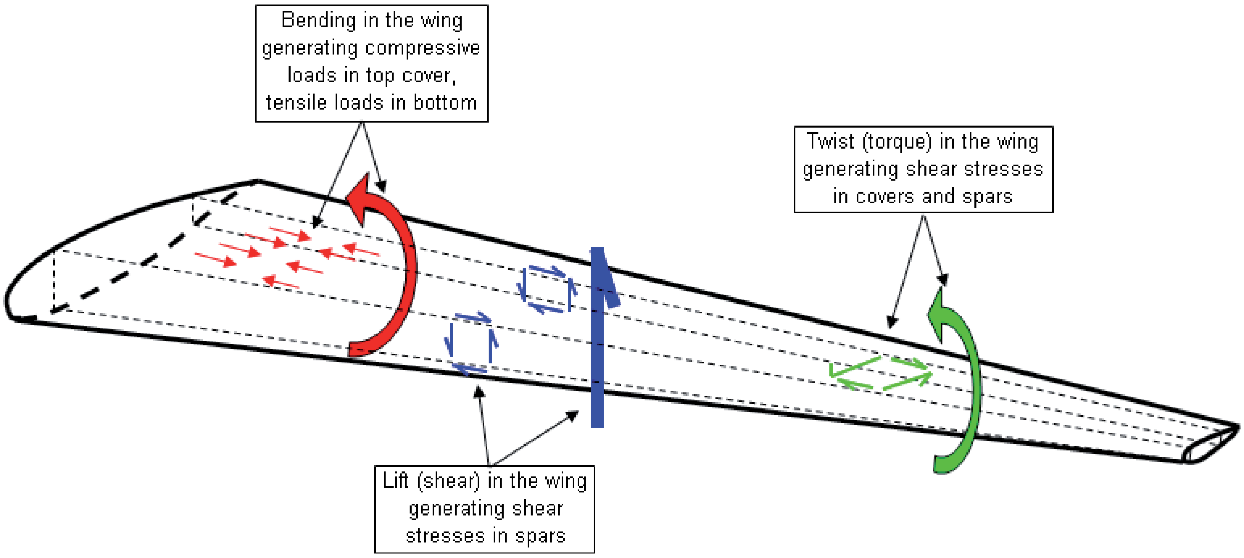

FIGURE 2. LOADING ON A WING BOX

strength under span-wise and shear loading and have looked at angles ranging between 30° and 45°. The studies have been confined to skin laminates and stringers - the stiffeners that resist buckling of the skins. These studies have shown that under predominantly tensile/shear loading there is a potential benefit of 7% in stiffness and strength for an angle of 35°. However, under compressive/shear loading, the benefits are less clear-cut, and strength can reduce at such angles. Thus, the use of these revised angles is likely to be suitable for the lower skin, for which the highest loads are tensile, but less so for the upper skin, which supports principally compressive load.

Similar benefits have been identified for the stringers for which, because they carry only small shear loads, a benefit both on the top and the bottom wing surfaces can be realised.

Further, a fringe benefit has been found to be reduced inter-lamina stresses at the bond between the stringers and the skins, alleviating a chronic concern regarding de-lamination at these susceptible joints.

From these studies we have been able to recommend initiation of a test programme to examine the strength of laminates with the angle of the angle plies ranging between 35° and 40°. These tests will assess damage tolerant residual strength (tensile and compressive strength following an impact) and bolted joint strength. Our recommendations are being taken up by Airbus as part of a wide-ranging test programme to assess the performance of different materials and lay-ups. Should this test programme confirm the suitability of such laminates, a 2-3% reduction in wing box structure weight is feasible.

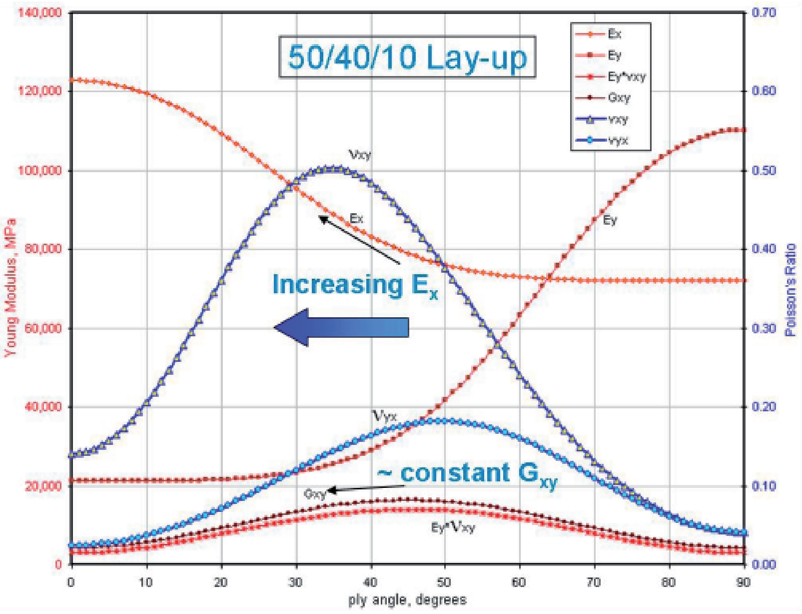

FIGURE 3. THE EFFECT OF REDUCING THE ANGLE OF THE ANGLE PLIES

5. Aero-elastic tailoring

Aircraft wings are flexible, and since their precise shape has a rôle in determining the aerodynamic loads applied to the wing, the control of the stiffness characteristics of the wing structure can be used to influence the externally applied loads, and hence the internal stress distribution. The adjustment of the stiffness characteristics of a structure to influence the magnitude and distribution of external and internal loads is termed "aero-elastic tailoring".

Carbon composite structures are particularly amenable to aero-elastic tailoring because the engineer can choose the orientation of fibres within the major components of the structure, thus strongly influencing the stiffness characteristics. In order to extract the greatest benefit from the use of carbon fibres for a wing structure, the adoption of aero-elastic tailoring should be considered with a view to minimising peak external loads and hence peak internal stresses. The reduction of the internal stresses and strains can be used to reduce structure weight. An extreme example of internal wing structure load relief is illustrated in Figure 4: the X29A forward swept wing demonstrator aircraft needed aero-elastic tailoring to mitigate the "divergent bending moment" that is inherent in a forward swept configuration. For a high aspect ratio (span/chord) wing, such as would be used for the NGCW, the greatest benefit may be accrued by a reduction in the bending moment near the wing root at high gust and manoeuvre loads. This reduction will result in a corresponding relief of span-wise stresses in the top and bottom skins, allowing either a decrease in the local skin thickness (and hence weight), or a decrease in overall wing thickness and sweep angle (again with reduced weight).

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: EC87–0182–14 Date: July 24, 1987 Photo By: NASA

X–29 in Banked Flight

FIGURE 4. AERO-ELASTIC TAILORING MADE THE X29A FORWARD SWEPT WING STABLE

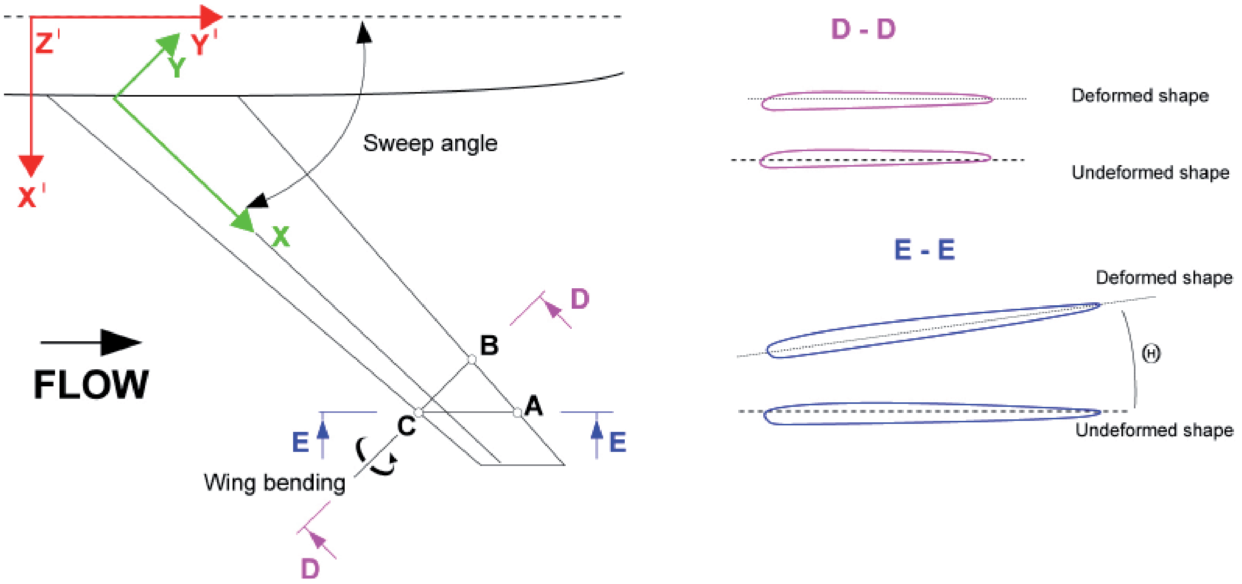

FIGURE 5. WASH-OUT OF LIFT AT THE TIP OF AN AFT SWEPT WING

The reduction of wing bending moment can be achieved by allowing lift to "wash-out" at the tip at high loads. This characteristic is achieved by introducing a coupling between wing bend and wing twist, and is one shared by aft swept wings, as shown in Figure 5. As composite wings are twice as stiff as their metallic counterparts, however, they "need some help" to achieve the same degree of wash-out and hence equivalent load relief. Atkins has been investigating the use of "unbalanced" lay-ups to achieve this goal.

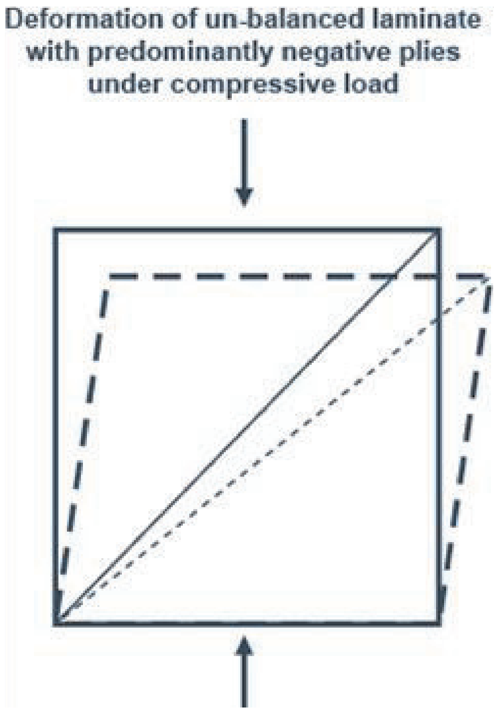

FIGURE 6. RESPONSE OF UNBALANCED LAY-UPS TO LOAD

By this means, there is an imbalance between the number of +45o and -45° plies in the skin lay-ups, leading to an imposed shear strain in the skins when a direct load is applied, as illustrated in Figure 6. Through the use of unbalanced laminates, compression in the top cover under an up-bending load can be arranged to generate shear in the cover, whilst tension in the bottom cover can generate shear in the opposite sense. These shears manifest themselves as twist of the overall box section. Therefore, the use of unbalanced laminates in the covers can be arranged to lead to bend/twist coupling in the wing box and hence the level of tip lift wash-out required to match or surpass that of an equivalent metal wing.

The Atkins work has shown that lay-ups with a moderate degree of imbalance can achieve twist/bend coupling that will result in significant increase in lift wash-out at the tip – equivalent to an additional 5° of wing sweep. Current analysis suggests, however, that the lay-ups should be used judiciously, as plain laminate strength calculations indicate that unbalanced lay-ups can have reduced strength characteristics under certain loadings. As is always the case with laminated composite aircraft structures, residual strength following damage and bolted joint strength drive the integrity of the structure, so Atkins has proposed unbalanced lay-ups as further additions to the Airbus materials test programme.

Although it is outside of the scope of our current remit, it is hoped that future work will allow us to assess the load relief that will be experienced across the wing by the use of these lay-ups. Further, the application of these techniques can be extended to aero/inertial-elastic tailoring – the control of an aerodynamic shape under combined aero and inertia loads. An application for this technology might be aero gas turbine fan blades, which could be designed to resist un-twisting across the running range of the fan.

6. Other studies

The examples that have been described derive from the novel laminates work programme, but a range of other developments are being carried forward both in this programme and in the rapid sizing arena. Typical examples of current studies are:

- Inter-lamina stress calculation to assess composite panel post-buckling and ramp rates used in varying thickness of laminate;
- Optimisation of wing box internal rib spacing and stiffener distribution;
- Rapid estimation of wing box internal loads and deflection;
- Simplified assessment of external wing box loads to support our aero-elastic tailoring studies.

These studies have been chosen to reinforce our knowledge and capability in areas of composite wing box design that represent a particular challenge.

7. Conclusions

Atkins' investment in the MDOW project has allowed us to explore facets of laminated composite design not readily investigated in the course of our normal work diet. The engineers involved in the project have had their eyes opened to the more esoteric possibilities that these advanced materials present. However, there is much to be done before the end of the NGCW programme, and we must maintain in our minds the critical words in that acronym: new technologies must be consistent with the next generation of civil aircraft.