Institution: University of Bath

Unit of Assessment:12: Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: Design and manufacture of composite wing structures - optimising performance and improving process

1. Summary of the impact

The A350-XWB is the first Airbus airliner to have composite wings, thereby reducing structural weight compared with the current generation of metallic wings. With over 700 orders for the aircraft, the company has placed great emphasis on the need to maximise performance benefits whilst mitigating risk associated with manufacture of the all-new wing. The Bath Composites Research Unit has supplied underpinning research to:

(1) Develop an algorithm that has been used to design the composite wing skins for optimised performance;

(2) Analyse the laminate consolidation process for the wing spars.

The impact of (1) is a direct saving of 1.0 tonne of fuel per typical flight compared with current metallic skins. This represents a total fuel saving of around 40,000 tonnes, over the design life of each aircraft. The impact of (2) is the achievement of satisfactory part quality for current production rates of spars valued at £1M each when equipped.

2. Underpinning research

Key researchers

Professor R Butler (Lecturer 1990-1999; Senior Lecturer 1999-2008; Reader 2008-2013; Professor since 2013); Professor GW Hunt (Professor 1995-2009; emeritus since 2009); Dr HA Kim (Lecturer 2001-2010; Senior Lecturer since 2010); Dr W Liu (Research Officer 2006-2013); Dr AT Rhead (Research Officer 2009-2012; Lecturer since 2012); Dr TJ Dodwell (Research Officer 2011-2013; Prize Research Fellow since 2013).

Ply layout algorithm for optimum design of A350-XWB wing skins

Context: The optimum (minimum weight) design of laminated skin panels, which vary from over 100 layers (plies) thick in some panels to 10 plies thick in others over a 30 m wing (root to tip) comprising more than 100 different panels, is a complex task requiring selection of:

(a) The laminate thickness in each panel; and

(b) The fibre orientation of each layer within each laminate.

For the standard four different fibre orientations (0, +45, -45 and 90 degrees) the number of possible stacking sequences in an *N*-layer stack over *M* unique panels is $(4^N)^M$. However, only a small subset of these will be manufacturable, in terms of providing continuity of material and satisfying practical design rules.

Underpinning research: Butler has developed composite panel optimisation algorithms in collaboration with Airbus for over 20 years. Early, prize-winning work on composite optimisation [1] demonstrated the optimum design of a complete wing skin panel, but without practical manufacturing constraints. The subsequent bi-level approach [2] showed that the stacking sequence, and hence laminate bending stiffness, of plies was of secondary importance to achieving the desired thickness of each fibre orientation, i.e. membrane stiffness. A Genetic Algorithm (GA) was used to establish discrete laminate solutions satisfying buckling and strength requirements. This was subsequently extended to include manufacturing constraints associated with a three-bay panel [3] to maximise ply continuity between adjacent panels of different thickness with a single, repeating sequence of plies, i.e. maintaining fixed percentages of each fibre orientation.

Low defect manufacture of A350-XWB rear spar

***Context*:** The laminated rear spar is made in 3 sections, each circa 10 m long and comprising complex shape and thickness variation. It is manufactured by robotic (Automated Fibre Placement) layering of 6.25 mm wide, 0.25 mm thick tows (tapes) containing unidirectional carbon fibres, pre-impregnated with uncured epoxy resin, over a male tool surface in a bandwidth of up to 100 mm. During the lay-up process, stacks of plies are consolidated at moderate temperature and pressure to remove trapped air between layers, forcing them to accommodate the imposed geometry of the tool. If these plies are prevented from slipping over each other, localised ply buckling or wrinkling can occur. Such wrinkling defects promote delamination, which can reduce the strength of the complete spar by up to 60%, leading to costly part rejection or, worse still, compromised component safety. Improvements in the process that reduce defect occurrence were hitherto empirically-driven.

***Underpinning research*:** The massive influence of manufacturing processes on the performance of laminates became apparent to Butler in 2011 when he undertook a part-time Royal Academy of Engineering Industrial Secondment at GKN Aerospace. During this period, he co-edited a special Royal Society issue, appearing in 2012 [4], and realised that the nonlinear modelling techniques for geological folding developed by mathematicians and engineers at Bath [5] could be adapted to model the pre-cured consolidation of laminates within the manufacturing process, and to predict the critical conditions for wrinkle occurrence. This led to a Bath-GKN sponsored one-year Knowledge Transfer Fellowship, from October 2011 to October 2012, for Dodwell during which geological folding models were adapted to predict fibre wrinkling during manufacture of laminated composite components using fundamental mechanics and energy minimisation techniques [6]. Much of this fellowship was undertaken at the GKN office of the National Composites Centre with visits to GKN's A350-XWB spar manufacturing facility during the pre-production development phase.

3. References to the research (* references that best indicate quality)

1*. R Butler. Optimum design of composite stiffened wing panels - a parametric study, 1995, Aeronautical Journal, **99**, No. 985, 169-177. (Can be supplied by HEI on request)
Awarded ***Royal Aeronautical Society's George Taylor prize*** *for the best paper published in the Aeronautical Journal on design, construction, production and fabrication (including structures and materials).*

2*. W Liu, R Butler and HA Kim. Optimization of composite stiffened panels subject to compression and lateral pressure using a bi-level approach, 2008, Journal of Structural and Multidisciplinary Optimization, **36**, No. 3, 235-245. DOI: 10.1007/s00158-007-0156-9

3. W Liu and R Butler. Optimum buckling design of composite wing cover panels with manufacturing constraints, 2007, Proceedings of 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Honolulu, Hawaii, AIAA paper, 2007-2215. DOI: 10.2514/6.2007-2215.

4. Philosophical Transactions of the Royal Society A, **370** (1965), Geometry and Mechanics of Layered Structures and Materials, Ed: CJ Budd, GW Hunt and R Butler.
DOI: 10.1098/rsta.2011.0539

5*. TJ Dodwell, GW Hunt, MA Peletier and CJ Budd. Multi-layered folding with voids, 2012, Philosophical Transactions of the Royal Society A, **370** (1965), 1740-1758.
DOI: 10.1098/rsta.2011.0340 [Ref 2]

6. TJ Dodwell, R Butler and GW Hunt. A variational model for the wrinkling of carbon fiber composites during consolidation, 2012, Proceedings 12th World Conference on Computational Mechanics, São Paulo. (Can be supplied by HEI on request)

4. Details of the impact

Specific impacts include: (1) New design methods for wing skins leading to savings in fuel cost and lower emissions; and (2) Improved manufacturing processes to achieve satisfactory quality in wing spars.

Airbus – performance improvement of wing skins: The Airbus A350-XWB wing skins were designed using a ply layout algorithm [A, B] developed by Liu, from the University of Bath, and Krog, from Airbus, whilst Liu was on secondment to Airbus between 2007 and 2009. The algorithm used was based on the fundamental principles established at Bath [2, 3], but extended to allow for variable percentages of each fibre orientation in each skin panel, whilst including practical manufacturing constraints. A permutation GA was used to shuffle layers such that continuity between adjacent panels was maximised whilst satisfying laminate design rules, leading to a patent application [B].

According to the Head of the Structural Optimisation Technology Centre at Airbus [C]:

> '… *the basis for the ply stacking algorithm, which today is used on A350-1000,was developed during the secondment of Liu to Airbus between 2007 and 2009. The algorithm, which brought together fundamental knowledge from the university with ideas and practical know-how from industry, is an integral part of a complex optimisation process that allows optimum design of wing skins whilst considering strength, design and manufacturing requirements. The complexity of this task was such that designs could not have been achieved without the algorithm.*'

The A350-XWB embodies the first composite wing for an Airbus airliner, entering service in 2014 with over 700 orders, at a list price of $254M per aircraft and an order deposit ranging from 5 to 35% of price, depending on time to delivery. The company expects the new skins to deliver component weight saving of 1.5 tonnes compared with metallic skins, leading to a fuel saving of 1.0 tonne per typical flight. This represents a total fuel saving of around 40,000 tonnes, over the design life of each aircraft, delivering a reduction in CO_2 emissions of 126,000 tonnes and a cost saving of $38M at current fuel prices.

GKN Aerospace – process improvements during wing spar manufacture: GKN Aerospace is a tier 1 supplier of high quality components to the aerospace primes, e.g. Boeing, Airbus, Rolls-Royce. As a risk-sharing partner, GKN manufactures the rear spar of the A350-XWB wing for Airbus. In order to achieve satisfactory part quality it is vital that defects, particularly in the form of fibre wrinkles, do not occur during manufacture.

The company has a history of build-to-print manufacture; however, in its on-going strategy to promote a more analytical approach to design and manufacture, GKN is jointly funding a Royal Academy of Engineering Research Chair in Composites Analysis for Butler, which commenced in March 2013. The aim of this Chair is to increase modelling, analysis and design, capability in order to optimise the efficient use of fibre-reinforced composite material and minimise the occurrence of defects during fully automated manufacture. In a News Release from GKN Aerospace [D], the Technical Director of GKN Aerospace explains:

> '*The advantages of composite structures are thoroughly proven. However, there remains much to gain from improving production processes to increase the speed and consistency of manufacture and to reduce production and material costs. The work of this research chair at Bath University will be of critical importance to the future success of the UK composites industry - as well as to the long term market position of GKN Aerospace. The results we achieve will strengthen the UK's broad industrial research landscape through the involvement of the National Composites Centre and a variety of UK-based academic networks.*'

During the secondment to GKN of Butler (RAEng funded, 2011) and then Dodwell (Bath-GKN funded, 2011-2012), project reviews [E] took place at which University achievements in modelling the wrinkling of laminates during production were reported. These models provided analytical insight into the formation of wrinkles in the A350-XWB wing spar. The Head of Analysis, GKN Aerospace states that [F]:

> '… *the work undertaken by Tim Dodwell assisted GKN to understand the fundamental mechanisms that initiate wrinkling defects in composite laminates, particularly those with complex geometry. This was the only mechanical simulation available to the company during pre-production. It allowed investigation of the consequences of process changes and further supported a number of process improvements to A350-XWB spar manufacture which have enabled us to achieve satisfactory part quality in production*.'

Specifically, the new analytical model supported the following two GKN process improvements, generated to prevent the occurrence of wrinkling defects during the A350-XWB spar development process:

(a) Manufacturing tools were introduced offset from the free edge of the spar laminate to keep consolidation pressure away from this edge. This effectively gave a vacuum channel around the spar edge and allowed the fibres and resin to move into this gap, thereby preventing wrinkling.

(b) The most critical influence was shown to relate to the viscosity of the resin material and therefore a hot de-bulk was introduced into the composite cure cycle to minimise viscosity during this period of maximum consolidation.

Wrinkling defects can lead to wholesale rejection of the part. Hence these process improvements contribute to the achievement of current (one aircraft per month) and future (13 per month) production rates, where each aircraft spar has an equipped (unequipped) value of approximately £1M (£100k).

5. Sources to corroborate the impact

A. W Liu and L Krog, L. A method for ply layout design and stacking sequence optimisation, 2008, 7th ASMO UK/ISSMO Conference on Engineering Design Optimization, Bath.

B. Patent Application Number 20110004451, Method of designing a composite panel, 2011.

C. Corroborative statement from Head of the Structural Optimisation Technology Centre, Airbus, 9 October 2013.

D. News Release from GKN Aerospace, 21 May 2013.

E Tectonics Review meetings: November 2011, Isle of White; February 2012, Bath; May 2012, National Composites Centre; July 2012, Filton.

F. Corroborative statement from Head of Analysis, GKN Aerospace, 3 October 2013.