**Institution:** University of Bristol

**Unit of Assessment:** 15 - General Engineering

**Title of case study:** Structural mechanics - enabling weight reduction and performance enhancement of composite aerospace structures

**1. Summary of the impact** (indicative maximum 100 words)

For aerospace vehicles, the development of new materials and structural configurations are key tools in the relentless drive to reduce weight and increase performance (in terms of, for example, speed and flight characteristics). The economic drivers are clear - it is widely recognised that it is worth approximately $10k to save one pound of weight in a spacecraft per launch and $500 per pound for an aircraft over its lifetime. The environmental drivers (ACARE 2050) are also clear - reduced aircraft weight leads to lower fuel burn and, in turn, to lower $CO_2$ and $NO_x$ emissions. With such high cost-to-weight ratios, there is intense industrial interest in the development of new structural configurations/concepts and enhanced structural models that allow better use of existing or new materials. Analytical structural mechanics models of novel anisotropic structures, developed at the University's ***Advanced Composites Centre for Innovation and Science*** (***ACCIS***), are now used in the industrial design of aircraft and spacecraft. Based on this research, a new, unique anisotropic composite blade, designed to meet an *Urgent Operational Requirement* for the MoD, is now flying on AgustaWestland EH101 helicopters that are deployed in Theatre. In addition, the new modelling tools and techniques have been adopted by Airbus, AgustaWestland, Cassidian and NASA and incorporated into LUSAS's finite element analysis software. These tools have, for example, been used to inform Airbus's decision to use a largely aluminium wing design rather than a hybrid CFRP/aluminium wing for the A380.

**2. Underpinning research** (indicative maximum 500 words)

The development of new structural configurations made from novel composite layups, and of the analysis tools to understand them, forms a key part of research into the performance and optimisation of composite structures. For this reason, Weaver (UoB since 1998) was recruited to the University's Composites Group (now ***ACCIS***) to develop new structural mechanics models for aerospace vehicles. His work, and that of his team within ***ACCIS***, has centred on the influence of interrelationships between geometric form and anisotropic material properties on structural performance in developing models for beams, plates and shells with physical insight and closed form solutions. The research has been part funded by Airbus and AgustaWestland and relevant consultancy work includes NASA Langley (2001-2009) and Cassidian (then, EADS Military Air Systems) (2006).

In 1999, Miller (UoB PhD student 1999-2002) developed thermoelastic models for predicting temperature build-up in carbon fibre reinforced plastic (CFRP) parts, when subjected to transient radiative and convective heating, typical of an aircraft sitting on a hot runway in a tropical climate. It was shown that the temperature build-up could exceed 80$^{O}$C, which, due to the thermal expansion properties of CFRP and aluminium, could result in significant fatigue stresses in the aluminium parts [1]. This fatigue issue contributed significantly to cancelling the hybrid Al/CFRP early concept wing structure in 2000-2001. Miller won the prestigious accolade of the Thomas Jefferson award for the best student paper at the American Institute of Aeronautics and Astronautics (AIAA) Structures, Dynamics and Materials Conference 2001, for this work.

Modern helicopter rotor blades are typically made from high specific stiffness materials, including CFRP, honeycombs and specialist polymeric foams. These allow better design of mass and stiffness distributions, which are crucial to ensure benign vibration characteristics. State-of-the-art methods relied on finite element analysis to calculate stiffness properties of realistic blade sections by estimating torsional, extensional, flap and lag bending stiffnesses. However, transverse shear effects and anisotropic coupling effects between bending and torsion, which are typically significant in anisotropic composite blades, were not included. From 2000-2002, Hill (UoB RA 1996-2006) and

Weaver developed an alternative finite element based method for calculating full 6x6 stiffness matrices, including all coupling effects as well as transverse shear, of fully anisotropic sections of arbitrary shape, composed of multiple materials. They demonstrated that the technique was highly useful to model the complex responses of helicopter rotor blades [2]. Building on this work, Lemanski (UoB PhD student 2000-2004) and Weaver developed an optimisation technique to minimise the mass of rotor blade sections by changing composite material properties, adjusting aerofoil skin thicknesses and altering the position of internal parts such as spars [3]. They also observed that the then state-of-the-art closed-form solutions did not quantify the effects of bend/twist coupling because they neglected the effects of vertical wall stiffness and foam, resulting in inaccurate and unusable results. Hence, they developed an anisotropic box model that quantified these effects resulting in much improved analytical modelling [4].

From 2000, Weaver developed a series of buckling and postbuckling solutions for anisotropic plates and cylindrical shells subject to compression, shear and combined loading. Based on early work on designing composite cylindrical shells under axial compression, Weaver was invited, in 2001, to be a consultant at NASA Langley. This consultancy continued until 2010 (grants totalling over $450k), where his insight, ideas and methods influenced high profile developments such as the ongoing Shell Buckling Knockdown Factor (SBKF) project. This project was proposed to address the innate conservatism in the design of cylindrical shell structures used in launch vehicles such as rockets and the space shuttle where, due to inherent imperfection sensitivity in the shell structures, high knockdown factors (safety factors) are traditionally used. Scientifically demonstrating that lower knockdown factors are justifiable allows a reduction in the vehicle's weight. Taking the widely acknowledged $10k cost-saving per pound of payload reduction, the estimated 10% weight saving in a structure weighing 1000 lbs leads to both a cost saving of £10M per launch. Particular insight shown by Bristol's work into anisotropic effects in cylindrical shells proved most valuable to the project. The work was summarised in the 46 page book chapter [5] having previously been published in AIAA journals, the International Journal of Solids and Structures and AIAA conference proceedings.

Cosentino (UoB PhD student 2006-10 and Airbus employee since 2006) and Weaver developed analytical structural models for the prediction of specific failure mechanisms of stiffened CFRP plates, representative of aircraft wing structures. They showed comparable accuracy to finite element models for predicting failure by stiffener debonding but with two orders of magnitude improvement in computational speed that allowed rapid sizing studies during the design process. This culminated in the conception of a new joint design, the *compound joint* [6], which using a combination of bolting and adhesives to separately facilitate the transfer of stresses by normal (Mode I) and shear (Mode II), respectively.

**3. References to the research** (indicative maximum of six references)


[1] *J. Miller and P.M. Weaver, 2003. *Temperature distribution in a composite box structure subject to Transient Heat Fluxes.* Journal of Thermophysics and Heat Transfer, 17(2), 269-277, dx.doi.org/10.2514/2.6762.

[2] G.F.J. Hill and P.M. Weaver, 2004. *Analysis of anisotropic prismatic sections*. The Aeronautical Journal, 108(1082), 197-205, (can be supplied upon request).

[3] S.L. Lemanski, P.M. Weaver and G.F.J. Hill, 2005. *Design of composite helicopter rotor blades to meet given cross-sectional properties*. The Aeronautical Journal 109(1100), 471-475, (can be supplied upon request).

[4] *S.L. Lemanski and P.M. Weaver, 2005. *Flap-torsion coupling in sandwich beams and filled box-sections*. Thin-Walled Structures 43(6), 923-955, dx.doi.org/10.1016/j.tws.2004.12.004.

[5] P.M. Weaver, 2008. *Anisotropic Elastic Tailoring in Laminated Composite Plates and Shells*. Book chapter in Buckling and Postbuckling Structures: Experimental, Analytical and Numerical Studies, Ed: B.G. Falzon & M.H. Aliabadi, World Scientific Press, ISBN-13: 978-1860947940.

[6] *V.A. Imperiale, E. Cosentino, P.M. Weaver and I.P. Bond, 2010. *Compound joint: A novel design principle to improve strain allowables of FRP composite stringer run-outs*. Composites: Part A, 41(4), 521-531, dx.doi.org/ 10.1016/j.compositesa.2009.12.010.

* References that best indicate the quality of the underpinning research.

**4. Details of the impact** (indicative maximum 750 words)

The impact of the University's work on developing new structural concepts and structural methods has been the use of the results and the tools by industry on a variety of aerospace applications. Here, we present six examples.

**1) A new structural concept that is now in-flight**

Lemanski and Weaver's unique anisotropic composite design [4] was used in the development of the BERP IV helicopter rotor blade in 2005-06 for AgustaWestland's EH101 helicopter. The Principal Rotor Engineer from AgustaWestland reported that "*the design, which uses unbalanced anisotropic angle plies at a specific fibre orientation, gives performance enhancement by coupling bending and torsion within the blade to reduce the loads experienced by the rotor control system. Eighty five of these blades, each with typical value of £100k, have been purchased by the UK MoD as part of an Urgent Operational Requirement in order to enhance the range and capability of the EH101 aircraft in Theatre"* [a]. Note that of the 85 blades, worth approximately £8.5M, 70 were ordered since 2008. They all continue to be flown and are used in situations where a heavy lift capability is required.

**2) A new analysis tool that influenced Airbus's A380 wing design**

Miller and Weaver's thermoelastic analysis [1] has been developed into a new structural analysis tool for Airbus. When designing the A3XX (which subsequently became the A380) aircraft, Airbus considered both aluminium and hybrid CFRP/aluminium wing designs. The Bristol-based tool was used by Airbus to inform the decision to use a largely aluminium, rather than hybrid, wing design [b]. As of July 2013 there have been firm orders for 262 A380s [c] with a market value of over $105B, based on an average list cost of $404M each [d].

**3) A new beam section analysis tool for AgustaWestland and then LUSAS's software**

Hill and Weaver's beam section analysis [2], for calculating 6x6 stiffness matrices for helicopter rotor blade sections, and the subsequent optimisation method [3] have been incorporated into AgustaWestland Helicopter's internal design codes (BSAP) [a]. The inclusion of these tools allows AgustaWestland to predict the response of rotor blades more accurately such that flight performance is improved via a reduction in deleterious vibration response whilst maintaining structural integrity. In addition to this improvement, Bristol's optimisation technique reduced the work of an engineer that previously took two weeks, to a matter of minutes [a].

Bristol's beam section analysis, which provides the 6x6 stiffness properties for finite element beams, was an improvement on the then current state-of-the-art techniques used in commercial finite element packages. It was incorporated into LUSAS's finite element software in 2008 [e], giving LUSAS the commercial advantage of being able to model the structural response of complicated multi-material beam sections.

**4) New buckling analysis tool for Cassidian**

Weaver's closed-form buckling solutions for plates and shells [5-6] are now a key part of Cassidian's LAGRANGE multidisciplinary optimisation software. The work was transferred to Cassidian via a £10k consultancy in 2006, and allows rapid analysis of the buckling capability of thin-walled sections such as wings and fuselages. As an example application, it has been used to help design the Airbus A350XWB aircraft structure [f]. The Airbus A350XWB is the first commercial Airbus aircraft to be mostly designed with composite materials. It had its maiden flight in July 2013 and first delivery is expected in mid 2014. So far 682 firm orders have been received [g] with a value of circa $173B, based on an A350-800 average list price of $254M [d]. Cassidian also intends to use these structural analysis models in the design of a European Unmanned Air Vehicle in 2014 [f].

**5. New structural failure analysis led to new structural concept for Airbus**

New analytical expressions for predicting the structural failure of stiffened wing panel structures [6] have been adopted in Airbus' design codes. Specifically the Senior Lead Stress for the A350-1000 Midbox states that *"the in depth understanding and methods developed during my PhD* [at Bristol] *helped Airbus refine their stringer runout design. The knowledge has been transferred* *transnationally throughout Airbus and Bristol's expertise is acknowledged. Furthermore, the papers published have been used as a starting point to define methods and allowables, helping Airbus prepare comprehensive Aircraft Certification Documents minimising the need for large tests"* [b].

These methods have supported the design of wings in commercial aircraft variants of the A350XWB: A350-900 and A350-1000 as well as the military aircraft A400M. As of August 2013, when it had its maiden flight, 174 A400M aircraft have been ordered [h]. Current savings of over £700k from virtual testing are estimated based on a typical cost of £35k per test. In addition to this cost saving, the new design based on Bristol's methods reduces the weight of a wing by approximately 10kg per wing [b] giving operational savings of around £14M based on the orders for A350XWB and A400M using a £800/kg cost to weight value.

This analysis subsequently allowed a new stringer-to-skin, aircraft wing joint design to be proposed [6]: *"Compound joints have become part of the certification training material.* [Bristol's] *2 and 1/2 dimension model was used for A380 checkstress. The way the Mode 1 and 2 contributions are decomposed in Stringer Run Out is used as a bonded joint pre-sizing method"* [b].

**6. New structural analysis for shells exploited by NASA**

NASA's Shell Buckling Knockdown Factor (SBKF) project was set up to "*help future heavy-lift launch vehicles weigh less and reduce development costs"* by generating new shell-buckling knockdown factors replacing the existing ones which *"date back to pre-Apollo-era studies - well before modern composite materials, manufacturing processes and advanced computer modeling"* [i]. New, more accurate and less conservative methods have now been developed for the design of shell structures for space launch vehicles. Estimated savings of the order of £10M/launch are expected with the first launch based upon these new design methods anticipated from NASA Wallops in 2014.

Weaver was consultant for NASA from 2001-2010 with support funds from NASA totalling around $450k. *[text removed for publication]*. [j].

**5. Sources to corroborate the impact** (indicative maximum of 10 references)


[a] Principal Engineer Rotors (Methods), AgustaWestland Helicopters.
[b] Senior Lead Stress, A350-1000 Midbox, Airbus.
[c] Airbus press release *Orders and Deliveries,* July 2013.
[d] Airbus press release *Airbus Aircraft 2013 Average List Prices*, January 2013.
[e] Director and Founder of Lusas finite element analysis – email correspondence.
[f] Senior Expert for Multidisciplinary Airvehicle Analysis and Design Optimization, Cassidian, Germany – email correspondence.
[g] Airbus press release *Orders, Deliveries, Operators*, July 2013.
[h] Airbus Military A400M homepage, downloaded August 2013.
[i] NASA - Marshall Star news article *2011 Marshall Space Flight Center Year in Review*, January 11, 2012.
[j] Senior Research Engineer and Principal Investigator of SBKF project, NASA Langley Research Center, USA.