Institution: University of Bath		
Unit of Assessment: B12 Engineering		
Title of case study: Improving quality in manufacture of high value aerospace parts		
Period when the underpinning research was undertaken: 2011 - 2019		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Richard Butler	Professor, previously Senior Research Fellow, Reader	September 1990 - present
Tim Dodwell	Prize Fellow, previously KTP Associate, KT Fellow	October 2011 - September 2015
Period when the claimed impact occurred: 2013 - 31 July 2020		
Is this case study continued from a case study submitted in 2014? Y		

1. Summary of the impact

The A350 is the first Airbus airliner with composite wings, saving 25% in fuel, CO_2 and operating cost compared with earlier metallic aircraft, with GKN supplying the rear spars - the backbone of the new wings. New modelling and testing methodologies created at the University of Bath have allowed GKN to: (i) meet the Airbus production rate increase from 1 per month in 2013 to 13 per month (and revenues of GBP150,000,000 per year) in 2018, and (ii) reduce spar scrappage, with direct savings of GBP11,000,000 per year and over 1,200tCO_2/year from reduced material wastage.

2. Underpinning research

Professor Richard Butler co-directs the Materials & Structures Centre (MAST). His group has developed composite analysis and design methods in collaboration with Airbus for over 25 years. Throughout 2011 he undertook a part-time Royal Academy of Engineering industrial secondment at GKN. At this time, GKN was carrying out pre-production trials for the manufacture of the composite Airbus A350 rear wing spar (see Fig. 1). This secondment established the need for model-based methods, both to reduce defects in production parts and to qualify the strength of such parts, leading to the award of Butler's RAEng-GKN Research Chair in Composites Analysis (2013-2023). Together, these methods would enable the increase in production rate required by Airbus whilst eliminating scrappage.

The Research Chair set clear objectives within a programme plan. Progress was reviewed at fortnightly meetings with GKN Engineering & Technology leads, with one appointed as Senior Visiting Researcher at the University of Bath, 2015-2021. Reports and papers were reviewed by GKN before publication and dissemination, generating underpinning research at University of Bath under the leadership of Richard Butler, in the following two areas:

Production process models and material characterisation *(extends research established for REF2014 Case Study to achieve REF2021 impact)*
A corner wrinkling model [1],(see Fig. 2 (a)), and a new Finite Element [2] were created by MAST researcher Tim Dodwell following his secondment to GKN in 2012. These methods provided new insights into the conditions required to avoid defect generation during laminate production. University of Bath MAST researchers then developed slip characterisation tests for pre-cured composite materials [3], locating the temperature that minimises slip resistance during viscoelastic consolidation of layers of carbon fibres, pre-impregnated with epoxy resin.

Structural performance models and test protocols *(new research for REF2021 impact)*
In 2014, MAST researchers developed a new test protocol [4] in which a tough resin layer is bonded to the edges of narrow witness specimens to alleviate interlaminar stress

concentrations (and numerical singularities) which are not present within wide, in-situ parts. This increased the strength of 'witness' specimens by up to 40%. An EPSRC Multiscale Modelling of Composites project discovered that micron-scale Finite Elements (FEs) are required to accurately predict critical stresses between layers in production parts with complex geometry and wrinkling defects, leading to between 10^7 and 10^9 Degrees of Freedom (DOF) for most practical applications (see Fig. 2 (b-c)). A new FE framework [5, 6], developed at the University of Bath, enabled solution of 10^9 DOF in minutes over 10^3 CPU cores on high-performance computers, providing insight into how the issue of manufacturing variability can be addressed by analysis, which consequently reduces testing time. In 2018, this research led to the award of the GBP6,900,000 CerTest EPSRC Programme Grant, a collaboration between the Universities of Bath, Bristol, Exeter and Southampton, on virtual certification of aerospace composites.

3. References to the research

[1] Dodwell, T, Butler, R & Hunt, G 2014, 'Out-of-plane ply wrinkling defects during consolidation over an external radius', *Composites Science and Technology*, vol. 105, pp. 151-159. https://doi.org/10.1016/j.compscitech.2014.10.007

[2] Dodwell, TJ 2015, 'Internal wrinkling instabilities in layered media', *Philosophical Magazine*, vol. 95, no. 28-30, pp. 3225-3243. https://doi.org/10.1080/14786435.2015.1034221

[3] Erland, S, Dodwell, TJ & Butler, R 2015, 'Characterisation of inter-ply shear in uncured carbon fibre prepreg', *Composites Part A - Applied Science and Manufacturing*, vol. 77, pp. 210-218. https://doi.org/10.1016/j.compositesa.2015.07.008

[4] Fletcher, TA, Kim, T, Dodwell, TJ, Butler, R, Scheichl, R & Newley, R 2016, 'Resin treatment of free edges to aid certification of through thickness laminate strength', *Composite Structures*, vol. 146, pp. 26-33. https://doi.org/10.1016/j.compstruct.2016.02.074

[5] Reinarz, A, Dodwell, T, Fletcher, T, Seelinger, L, Butler, R & Scheichl, R 2018, 'Dune-composites – A new framework for high-performance finite element modelling of laminates', *Composite Structures*, vol. 184, pp. 269-278. https://doi.org/10.1016/j.compstruct.2017.09.104

[6] Butler, R, Dodwell, T, Reinarz, A, Sandhu, A, Scheichl, R & Seelinger, L 2019, 'High-performance dune modules for solving large-scale, strongly anisotropic elliptic problems with applications to aerospace composites', *Computer Physics Communications,* vol. 249, 106997. https://doi.org/10.1016/j.cpc.2019.106997

4. Details of the impact

The A350 spar manufacturing process adopted by GKN is the most demanding application of Automated Fibre Placement (AFP) of its time. Spars are assembled from three 10m-long sections, as in Fig. 1(a), where each spar is made from 0.25mm thick layers of unidirectional carbon fibre composite. AFP robots deposit narrow tapes over complex male moulds, see Fig. 1(b), to produce parts of specified thickness, varying from tens to hundreds of layers. The so-called preforms are then cured under controlled temperature and pressure to achieve 10% consolidation (thickness reduction). Layers must be free to slide over each other, otherwise wrinkles will occur in regions of high curvature, see Fig. 2 (a) and (b). Spar sections are qualified by cutting narrow 'witness' sections from production parts and mechanically testing these for strength to failure.

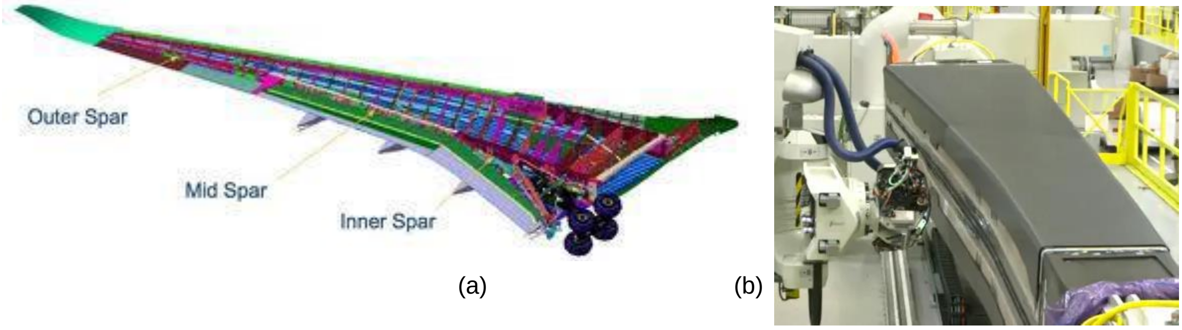
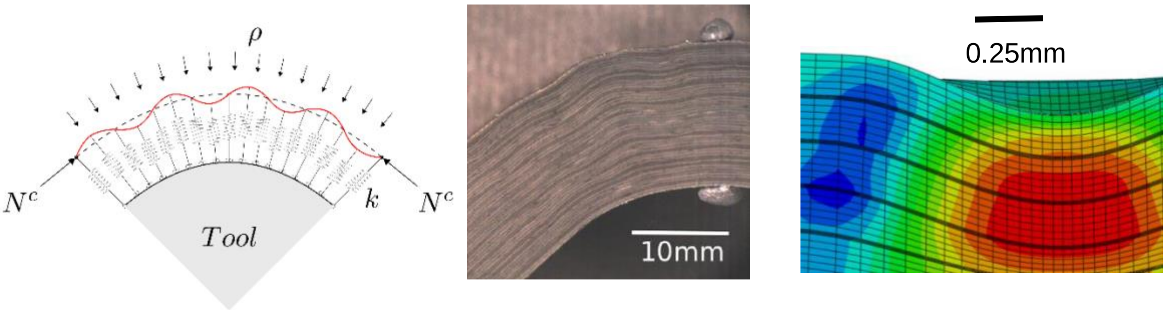


Fig. 1. A350 wing showing 3-part rear spar: (a) within wing and (b) during manufacture (of 10m inner spar).



(a) (b) (c)

Fig. 2. Corner wrinkling. (a) Bath process model: slip-resisting forces N^C can give rise to buckling when laminate with consolidation stiffness k is subject to autoclave pressure ρ. (b) Witness section cut from wrinkled spar. (c) FE resolution required for accurate strength assessment.

The impact of Bath research originates from: manufacturing process improvements, part qualification, and a shared research culture, as follows.

Improvements to manufacturing process for A350 spar
The corner wrinkling model [1] provided analytical insight into the formation of wrinkles in the A350 wing spar. Specifically, the new model led to the following 2 process improvements, described in GKN Manufacturing Build Instructions [A], which prevent the occurrence of wrinkling defects during production:

(a) Tools were introduced which were offset from the free edge of the spar laminate to ensure consolidation pressure was kept away from this edge. This provided a vacuum channel around the spar edge and allowed the fibres and resin to slide into this gap, thereby preventing wrinkling.

(b) The most critical influence was shown to be minimization of the viscosity of the resin material when consolidation occurred, and so a high-temperature dwell was introduced when the part was under autoclave pressure. The critical conditions for this dwell were obtained using new test methods established by MAST researchers [3].

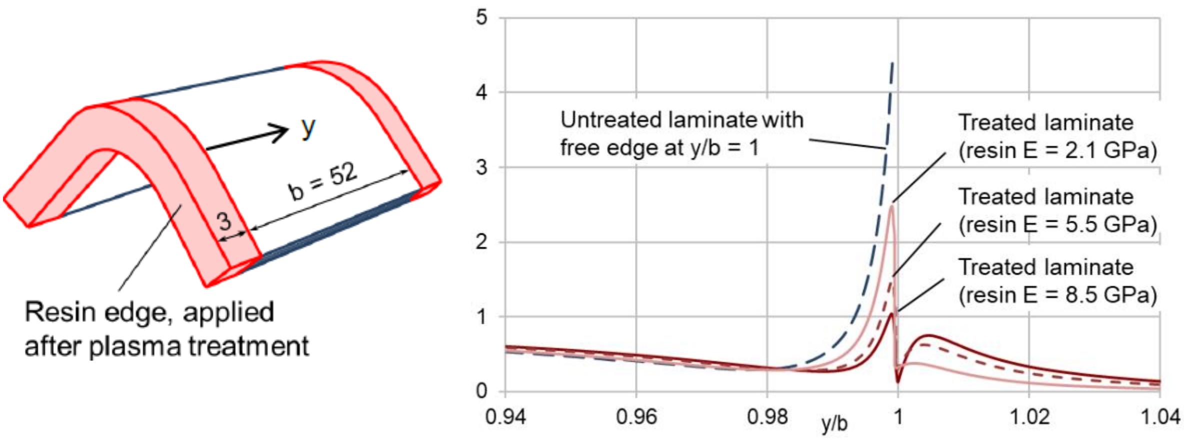
According to the Vice President Engineering Technology & Quality at GKN, the impact of these innovations, from 2013 to 2018, is that [A]:

> *"Together, these steps – supported by Bath's fundamental research - have enabled us to meet the ramp-up in production rates for the A350, which was more aggressive than previous models, to meet commercial requirements due to the large investment in*

automation. This rate represents a contribution to annual revenue in excess of GBP150,000,000".

Qualification of A350 spar strength

The strength of spar corners is tested by bending the corner open until failure, which was expected to arise near the mid-thickness but, in practice, occurred throughout the thickness of witness sections. Detailed FE analysis showed that this was due to an edge effect, that acts as stress concentration, which does not arise in the wing. Bath researchers developed a new edge treatment process [4] in which a tough resin layer is bonded to the exposed edges of witness specimens, see Fig. 3 (a), to alleviate the edge effect, see Fig. 3 (b), and produce repeatable failure near the mid-thickness, which is more representative of *in situ* loading within the wing.



(a) (b)

Fig. 3. Edge treatment of spar corners: (a) geometry (in mm) and (b) reduction in normalised inter-laminar tensile stress at edge (y = b), with varying elastic modulus of edge resin.

This process was accepted by airworthiness authorities and customer certification engineers [A], and the impact of this work to GKN is that [A]:

> *"This protocol helped us to salvage all defective spars which would otherwise have been scrapped, … leading to an annual saving of GBP11,000,000. The effect of edge treatment was validated using MAST numerical modelling expertise, which we were able to use as evidence for customer approval of qualification".*

saving 1,200tCO_2/year from reduced material wastage from 2018 onwards.

Shared research culture

According to GKN [A]:

> *"…the fundamental research developed at the University of Bath by MAST has led to significant improvement in our manufacturing processes, providing a positive impact, not only in financial terms, but also by achieving target productivity and enabling zero tolerance to defects during manufacturing, in line with our corporate strategy. As a direct consequence of impact from MAST research, we are delighted to have recently extended Richard's RAEng/GKN Research Chair, and we anticipate new innovations leading to new business opportunities as we collaborate with MAST as core partners in our new Global Technology Centre*".

5. Sources to corroborate the impact

[A] Corroborating letter from Vice President Engineering Technology & Quality, GKN Aerospace, 13 December 2019; corroborating email and attached report from Stress Technical Authority, GKN Aerospace, 13 December 2019.