Institution: University of Bristol		
Unit of Assessment: 12) Engineering		
Title of case study: Novel simulation and manufacture methods deliver advances for Rolls-Royce's next generation composite aeroengine fan system		
Period when the underpinning research was undertaken: 2000-2016		
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:**
Stephen Hallett	Professor in Composite Structures	11/2000-present
Michael Wisnom	Professor of Aerospace Structures	11/1987-present
Giuliano Allegri	Reader in Composite Structures	10/2007-07/2014, 02/2018-present
Mehdi Yasaee	Research Associate in Experimental Characterisation of Composites	11/2011-01/2016
James Lander	Research Associate	12/2008-08/2011
Wen-Guang Jiang	Research Fellow	03/2003-12/2007
Period when the claimed impact occurred: 2014-July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

New simulation tools and manufacturing advances developed by the Bristol Composites Institute have reduced the development cost and weight of Rolls-Royce's next generation of turbofan aeroengine, the UltraFan®, and increased components' resilience to damage. UltraFan® will use a novel Carbon-Titanium composite fan system to deliver a 25% reduction in fuel consumption compared to early 2000s aero-engine technology. The specific University of Bristol contribution has been to the prediction and mitigation of impact (bird-strike and trailing blade) damage in composite fan blades and containment casing, an essential requirement for engine certification and aircraft safety. The new manufacturing method invented is deployed in the Rolls-Royce Filton pre-production facility, creating and safeguarding jobs as well as leading to developments in the supply chain.

2. Underpinning research

Carbon-fibre reinforced composites have many advantageous properties for aerospace applications. Their high specific stiffness and strength allow for weight efficient, high performance structures. However, in their most common format, where the reinforcing fibres are pre-impregnated with resin and then laid up to form a laminate, the reinforcing fibres only lie in the component in-plane directions. Composite laminates thus lack fibre reinforcement through the thickness, where the strength is controlled only by the relatively weak polymer matrix. Consequently, laminated fibre-reinforced structures are prone to fail due to ply dis-bond (i.e. delamination), which usually occurs at much lower loads than those required to break the strong in-plane carbon fibres, particularly under impact. Understanding, predicting, and preventing delamination is therefore of great importance for the structural integrity of composite components. Research within the Bristol Composites Institute (http://www.bristol.ac.uk/composites/) at the University of Bristol (UoB) has made profound advances in both predicting the occurrence of delamination and mitigating the effects of delamination damage.

CZM: predicting the occurrence of delamination

Between 2000 and 2013, Jiang, Hallett and Wisnom developed a novel cohesive-zone model (CZM) interface element for use in explicit dynamic finite element analysis to predict delamination initiation and propagation under quasi-static and impact loads [1,i,ii]. This modelling technique represented a significant advance over the then more widely used stress-based failure criteria or Virtual Crack Closure Technique (VCCT) in that it combined stress and fracture energy criteria, allowing for the modelling of both the initiation and propagation of delamination cracks in a single computer analysis. This modelling capability was further improved by introducing the enhancement of the CZM element's strength and fracture toughness properties under transverse compressive loads [2], which is an important feature for the Rolls-Royce applications and unique to the UoB CZM formulation.

Direct Insertion Method: mitigating delamination damage
Predicting the occurrence of delamination is extremely important for component design calculations, however, ultimately one wants to avoid or control delamination damage. From 2011 to 2016, Yasaee, Hallett, Lander and Allegri undertook a programme of work to investigate the fundamentals of delamination delay and arrest provided by Z-pin bridging, a method of through-thickness reinforcement (TTR) achieved by inserting pre-cured carbon fibre rods into a composite laminate during manufacture. Their research resulted in new, detailed understanding of the mixed-mode behaviour of such reinforcement [3,4], as well as the invention of a new method for introducing Z-pin TTR in laminates: the Direct Insertion (DI) method [5]. The DI method enables the reinforcement of thick laminates (55+ mm) with far higher accuracy and less process-induced defects than any other existing TTR insertion method. A novel CZM interface element formulation, which represents an extension of the approach in [1], was also introduced to predict the behaviour of delaminations bridged by Z-pins within the framework of finite element analysis [6].

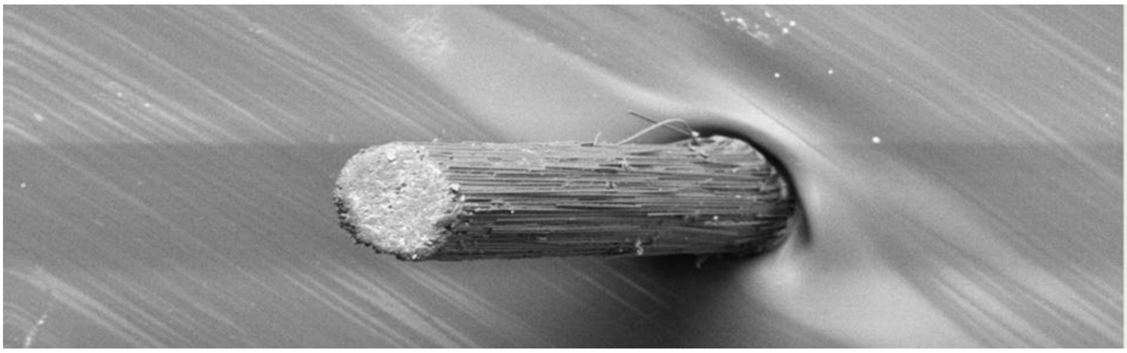

Figure 1. Scanning electron micrograph of a carbon-fibre Z-pin, revealed after delamination failure

3. References to the research

[1] **Jiang WG, Hallett SR**, Green BG, **Wisnom MR** (2007). A concise interface constitutive law for analysis of delamination and splitting in composite materials and its application to scaled notched tensile specimens, *International Journal for Numerical Methods in Engineering*, **69(9)**, pp.1982-1995, https://doi.org/10.1002/nme.1842

[2] Li X, **Hallett SR, Wisnom MR** (2008). Predicting the Effect of Through-Thickness Compressive Stress on Delamination using Interface Elements, *Composites Part A: Applied Science and Manufacturing,* **39(2)**, pp.218-230, https://doi.org/10.1016/j.compositesa.2007.11.005

[3] **Yasaee M, Lander JK, Allegri G, Hallett SR** (2014). Experimental characterisation of mixed mode traction–displacement relationships for a single carbon composite Z-pin, *Composites Science and Technology*, **94(9)**, pp.123-131, https://doi.org/10.1016/j.compscitech.2014.02.001

[4] **Allegri G, Yasaee M**, Partridge IK, **Hallett SR** (2014), A novel model of delamination bridging via Z-pins in composite laminates, *International Journal of Solids and Structures*, **51(19-20)**, pp.3314-3332, https://doi.org/10.1016/j.ijsolstr.2014.05.017

[5] **Lander JK**, *A method of providing through-thickness reinforcement of a laminated material*, Patent no. EP2581201B1 (2016), US8893367B2 (2014), CN103042732B (2016)

[6] Mohamed G, **Allegri G, Yasaee M, Hallett SR** (2018), Cohesive element formulation for Z-pin delamination bridging in fibre reinforced laminates, *International Journal of Solids and Structures,* **132-33**, pp.232-244, https://doi.org/10.1016/j.ijsolstr.2017.05.037

Grants

[i] **Wisnom MR** (PI), *Modelling damage development in notched composites*, EPSRC, 2000-2002, GBP81,429
[ii] **Wisnom MR** (PI), *Scaling Effects in Notched Composites*, EPSRC, 2003-2006, GBP194,717

4. Details of the impact

In February 2014, Rolls-Royce announced the UltraFan® engine as its next-generation product for twin-aisle wide-body aircraft [A]. Forecast to enter the market towards the end of this decade, UltraFan® will achieve a 25% reduction in fuel consumption compared to the Trent-family engines of the early 2000s [B]. The weight-saving Carbon-Titanium (CTi) composite fan system is one of the key innovations that Rolls-Royce will deploy in UltraFan® to reduce fuel burn and emissions. *"A Rolls-Royce fan system made with carbon-fibre composites can save almost 700 kg per aircraft"* [C]. The use of composite materials is an essential enabling technology and a critical part of the solution to design a fan blade at this scale, which is not feasible using the more conventional titanium metal alloy [D]. Besides delivering one of the world's most energy efficient aero engine fan systems, at 140 inches (3.56m) in diameter, the CTi composite fan is also the world's largest fan blade ever produced for civil aerospace [B], which entails significant design challenges.

To achieve a commercially viable composite fan system solution, Rolls-Royce's development of the CTi fan system has drawn on two key developments by the University of Bristol: cohesive-zone modelling (CZM) [1,2], and through-thickness reinforcement (TTR) direct insertion (DI) [3,5]. These technologies have not only enabled Rolls-Royce to deliver a technical design solution, but they have also delivered substantial cost savings [D,F].

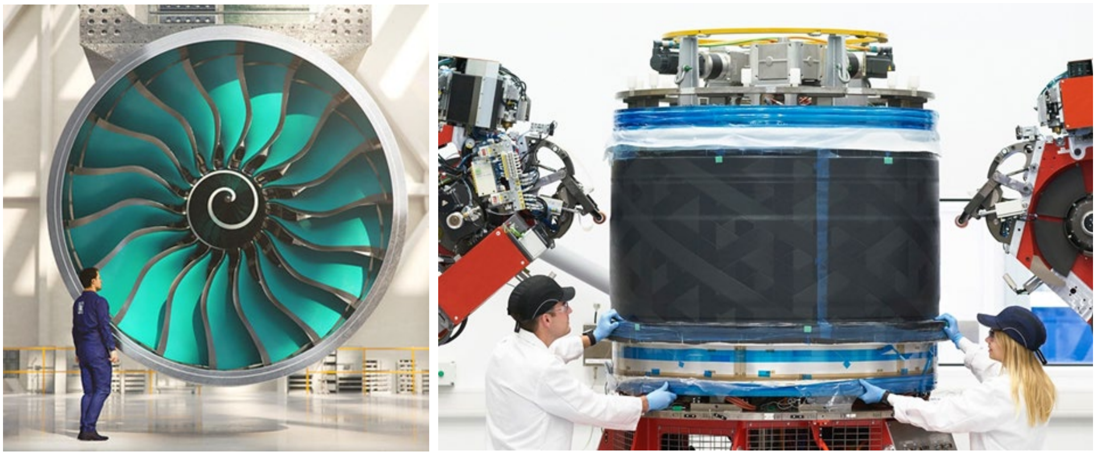

Figure 2. UltraFan CTi fan blade set and casing under production

Technology transfer between UoB and Rolls-Royce is conducted via their strategic partnership, the Composites University Technology Centre (UTC), established in 2007. The technology readiness levels (TRL) of analysis methods, including software implementation, are assessed via a formalised series of gated technical reviews [E]. Manufacturing processes follow an adapted process known as Manufacturing Capability Readiness Level (MCRL). The achievement of TRL4 (UTC/laboratory-scale testing) is assessed by the "Critical Capability Acquisition Review" (CCAR); TRL6 (full-scale system demonstration) by a "Capability Acquisition Review" (CAR); and TRL8 is achieved at the end of the design process and the start of pre-production prototyping.

As of July 2020, the status of the UltraFan® engine and its CTi fan blade system is that the design of the demonstrator is complete, and manufacturing has begun, with ground running engine tests planned for 2021. "*This is a major achievement for any new engine programme and* *would not have been possible without the University of Bristol's research contribution to the technology used in its CTi fan blade system*" - Rolls-Royce Chief of Technology (Fans and Compressors) [F].

CZM Technology helps ensure the impact capability of the UltraFan® CTi Fan system and deliver cost savings for Rolls-Royce

After the initial development of UoB's CZM technology for composites delamination [1,2], the interface element software was transferred to Rolls-Royce in 2014 and went through a successful formal CCAR review at Rolls-Royce and was certified at TRL 4 in April 2017 [D]. This was followed by extensive trials carried out by the Rolls-Royce Impact Group, which led to the achievement of TRL 6 in June 2017. The Bristol CZM technology is now embedded into Rolls-Royce's production version of the explicit finite element solver LS-DYNA. It is considered to be at TRL 8, because it is employed for the simulation of impacts on full-scale components, i.e. bird strike analysis of prototype fan blades [D].

A key example of Rolls-Royce's use of UoB's CZM technology was in the design of the CTi fan blade [text removed for publication]. "*In November 2018 the UltraFan® development blade successfully passed three different variants of the* [text removed for publication] *test, thanks to the upfront computational modelling that was undertaken*." – Rolls-Royce, Chief of Technology – Fans and Compressors [D].

The next test in the CTi Fan System certification strategy was the containment test, where a full set of 18 blades is run up to full engine take-off speed and a single fan blade is released to show it does not breach the protective containment casing. Again, the CZM modelling technology has been used extensively to model the UltraFan® engine containment casing [text removed for publication] to de-risk this exceedingly complex and expensive test [text removed for publication]. In the 3rd quarter of 2019, the containment test was successfully passed at the Rolls-Royce test facility in Dahlewitz, Germany [D]. Overall, it is estimated that 21,000 hours of analysis run-time have been completed on Rolls-Royce computers using UoB's CZM technology [D].

Direct Insertion Method (Z-pins) leads to cost savings, becomes baseline method for fan blade production, and creates new business for the Rolls-Royce supply chain

The second UoB-developed technology adopted by Rolls-Royce for UltraFan® is the direct insertion (DI) method [5] for inserting through-thickness reinforcement (TTR), i.e. Z-pins, into the CTi fan blade. TTR is essential for managing the occurrence of delamination [3] during high-energy impact events, such as bird strikes. This allows the engine to meet stringent certification requirements for safe shutdown or run-on, e.g. EASA Airworthiness Code CS-E 800 'Bird Strike and Ingestion' [G]. [Text removed for publication].The DI technology was industrialised at the UK National Composites Centre (NCC) between 2012 and 2016, using the UK supply chain (Bowyer Engineering Ltd.) to automate the process. It achieved a 24 times improvement in rate and cost over the baseline insertion method. The DI method achieved MCRL4 in 2015, when a full-scale fan blade was pinned at the NCC for the first time [F].

In 2016, the DI technology was transferred to the Rolls-Royce/CTAL (Composite Technology and Applications Ltd) facility, located on the Isle of Wight, supported by a GBP7.4M funding contribution from the UK government [H], where the technology was integrated into the development fan-blade manufacturing process. In 2018, the Composites Technology Facility (CTF), a new pre-production factory for CTi fan blades and containment casings, was created at the Rolls-Royce Filton site, with a GBP25M investment, securing over 150 jobs in the Bristol area, including 30 transferred from the Isle of Wight facility [C].

For the CTF facility, a third generation DI manufacturing cell was acquired from Accudyne, a US-based company that builds first-of-a-kind automation solutions for novel manufacturing processes, with an annual turnover of USD10M. The DI equipment manufacture created a new stream of business for their company, which required an internal investment of [text removed for publication] to develop prototype equipment, and in turn has created an opportunity for future business with Rolls-Royce in excess of [text removed for publication]. To facilitate the new relationship with Rolls-Royce, Accudyne increased their Engineering staff in the US by 2 people and set up a UK subsidiary in 2018 to provide local support and manufacture new DI machines, which will be required when the Rolls-Royce fan blade goes into production [I]. The Accudyne CTF DI facility has demonstrated insertion "Right First Time" metrics never falling below 99.95% [F].

[Text removed for publication].

[Text removed for publication] prototype fan blades have now been pinned by Rolls-Royce/CTAL, with many having undergone comprehensive testing and quality inspections, including successful certification tests. The DI reinforced fan blade is planned to reach TRL6 by Dec 2020. In addition to the quality benefits outlined above and its enabling capability, it has also been assessed that the UoB-developed DI insertion technology has delivered a cost saving of [text removed for publication] per engine to Rolls-Royce [F]. DI has been declared as the baseline method for future production of fan blades for engines of the UltraFan® family [F]. Overall, it is estimated that [text removed for publication] has been invested in the industrialisation of the DI technology [F].

5. Sources to corroborate the impact

[A] Rolls-Royce (26 February 2014) – Press Release, *Rolls-Royce shares next generation engine designs* [Accessed 8 June 2020]
[B] Rolls-Royce (11 February 2020) – Press Release, *Rolls-Royce starts manufacture of world's largest fan blades – made of composite material – for next-generation UltraFan® demonstrator* [Accessed 8 June 2020]
[C] Rolls-Royce (9 January 2020) – Press Release, *Rolls-Royce opens new facility in Bristol, UK to develop components for cleaner, quieter, more-efficient jet engines* [Accessed 8 June 2020]
[D] Rolls-Royce (2020) – Corroborating statement (CZM), Chief of Technology, Fans and Compressors
[E] Evidence to House of Commons by Rolls-Royce on Technology Readiness Level [Accessed 8 June 2020]
[F] Rolls-Royce (2020) – Corroborating statement (TTR), Chief of Technology, Fans and Compressors
[G] EU Aviation Safety Authority (14 December 2018) – Certification Specifications and Acceptable Means of Compliance for Engines Amendment 5 [Accessed 21 Sept 2020]
[H] Rolls-Royce (18 March 2015) – Press Release, *Rolls-Royce to create Composite Technology Hub in Bristol* [Accessed 8 June 2020]
[I] Accudyne Systems Inc. (2020) – Corroborating statement, CFO