Institution: University of Bristol		
Unit of Assessment: 12) Engineering		
Title of case study: Wind turbine blade and aerospace composite component manufacture benefits from advanced numerical simulations		
Period when the underpinning research was undertaken: 2001-2016		
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:**
M R Wisnom	Prof. Aerospace Structures	11/1987-present
K D Potter	Prof. Composites Manufacture	03/2002-03/2020
N Ersoy	Research Associate	03/2002-05/2004
S R Hallett	Prof. Composite Structures	11/2000-present
J P-H Belnoue	Research Fellow	03/2011-present
J Kratz	Lecturer	10/2013-present
Period when the claimed impact occurred: 2014-31 July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Reduced time to market, cost savings in production, and reduced risk of out-of-spec products for the wind energy and aerospace sectors are the most significant impacts arising from two University of Bristol research programmes on composite manufacturing. The knowledge and numerical algorithms produced by this research facilitated the creation of LMAT ltd, a consultancy employing 4 people with an annual turnover of GBP0.5M. LMAT commercialised the know-how into a simulation software plug-in (Ansys Composites Cure Simulation - ACCS) that has been used to achieve right-first-time design of mould tools for the Airbus A350 wing spar, Vestas wind turbine blades and Rolls-Royce aero-engine components currently in production. The use of ACCS reduced the development cycle for Airbus aircraft components by at least six months.

2. Underpinning research

Composite materials are becoming the material of choice for large aerospace and wind energy structures due to their light weight, high specific strength and stiffness, and good corrosion and fatigue-resistant properties. However, manufacturing large-scale structures remains a challenge due to the mechanisms that cause residual stresses and part distortions, such as thermal expansion, cure shrinkage of the resin, consolidation and tool-part interaction. These mechanisms usually act collectively throughout the manufacturing process and can lead to significant changes to the geometry of the part from the original/intended design, see Figure 1.

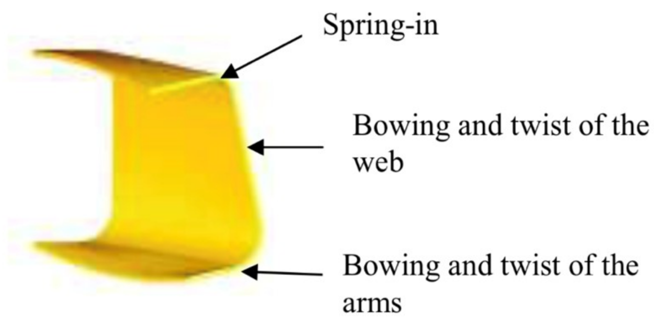

Figure 1. Distortion modes of an aircraft wing spar C-section

Two University of Bristol research projects undertaken within the Bristol Composites Institute have significantly increased the understanding of composites processing, leading to the development of numerical tool sets for predicting manufacturing deformations:

- COMPAVS – Composite Processing Avoiding Variability and Stress;
- DEFGEN – Defect Generation Mechanisms in Thick and Variable Thickness Composite Parts – Understanding, Predicting and Mitigation.

The COMPAVS project [i] (Wisnom, Potter, Ersoy – 2001-2004) provided a fundamental understanding of the mechanisms generating residual stresses and distortions (Figure 1), the different roles of cure shrinkage and thermal stresses, and the importance of tool-part interaction [1]. For the first time, it became possible to measure the way in which stresses develop due to the action of these mechanisms during the cure process [1]. Several novel experimental techniques were developed including a method to determine in-situ cure shrinkage more simply and accurately than previously possible, by direct measurements on a laminate during cure [2]. A new numerical simulation approach was also generated as a part of this project, where algorithms based on the observed physical phenomena were embedded into engineering software. This modelling approach was applied to real components, much larger than the laboratory scale tests it was trialled on, and was shown to be capable of accurately predicting final part geometry [3]. This was able to account for the important effect of part thickness on spring-in, the geometry change of a curved section, which was not predicted by previous simple analyses [3].

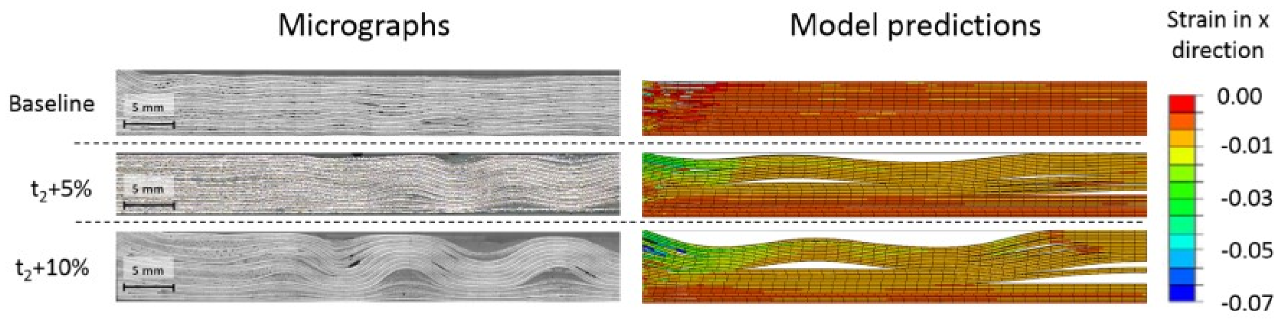

Figure 2. Manufacturing induced wrinkle defects and their prediction

The DEFGEN project [ii] (Hallett, Belnoue, Potter, Kratz – 2013-2016) investigated the consolidation of uncured composite materials pre-impregnated with epoxy resin (pre-preg) and its role in the formation of defects during composite manufacture. The project developed new testing methods to accurately measure the compaction of uncured pre-preg at various temperatures, rates and length scales [4]. For the first time, the existence of multiple flow mechanisms (shear and percolation) in one material type was identified and characterised. In addition, reaction kinetics, conductivity, heat capacity and glass transition temperature measurements were obtained for the epoxy resin system under investigation [5]. To model the compaction and flow behaviour, new theoretical models and numerical algorithms were developed [6]. Models for the curing behaviour of the resin system were also generated [5] The algorithms were embedded in the commercial finite element software Abaqus as a user subroutine which accurately predicted a range of fibre path defects that occur during thick composite component manufacture. These models were validated against a range of experimental data (see Figure 2). The models were able to produce their accurate predictions using only independently measured material properties, part geometry and process parameters, with no fitting or calibration to the experiments required.

3. References to the research

1. **Wisnom MR**, Gigliotti M, **Ersoy N**, Campbell M, **Potter KD** (2006). Mechanisms generating residual stresses and distortion during manufacture of polymer–matrix composite structures, *Composites Part A: Applied Science and Manufacturing*, **37:4**, pp. 522-529, https://doi.org/10.1016/j.compositesa.2005.05.019
2. Garstka T, **Ersoy N**, **Potter KD**, **Wisnom MR** (2007). In situ measurements of through-the-thickness strains during processing of AS4/8552 composite, *Composites Part A: Applied Science and Manufacturing*, **38:12**, pp. 2517-2526, https://doi.org/10.1016/j.compositesa.2007.07.018

3. **Ersoy N**, Garstka T, **Potter K**, **Wisnom MR**, Porter D, Stringer G (2010). Modelling of the spring-in phenomenon in curved parts made of a thermosetting composite, *Composites Part A: Applied Science and Manufacturing*, **41:3**, pp. 410-418, https://doi.org/10.1016/j.compositesa.2009.11.008
4. Nixon-Pearson OJ, **Belnoue JPH**, Ivanov DS, **Potter KD**, **Hallett SR** (2017). An experimental investigation of the consolidation behaviour of uncured prepregs under processing conditions, *Journal of Composite Materials*, **51:13**, pp. 1911-1924, https://doi.org/10.1177%2F0021998316665681
5. Mesogitis T, **Kratz J**, Skordos AA (2019) Heat transfer simulation of the cure of thermoplastic particle interleaf carbon fibre epoxy prepregs, *Journal of Composite Materials*, **53:15**, pp. 2053–2064, https://doi.org/10.1177%2F0021998318818245
6. **Belnoue JPH**, Nixon-Pearson OJ, Ivanov D, **Hallett SR** (2016). A novel hyper-viscoelastic model for consolidation of toughened prepregs under processing conditions, *Mechanics of Materials*, **97**, pp. 118-134, https://doi.org/10.1016/j.mechmat.2016.02.019

Grants
[i] **Wisnom MR** (PI), *Composite Processing Avoiding Variability and Stress (COMPAVS)*, EPSRC/Qinetiq, 2001-2004, GBP336,000
[ii] Long A (PI) Partridge IK, Mills AR, Pickering SJ, **Potter K**, Schubel P, Johnson M, Eichhorn S, Potluri P, **Wisnom M**, **Hallett SR**, Warrior N, Soutis C, Skordos AA (CI), *EPSRC Centre for Innovative Manufacturing in Composites*, EPSRC EP/I033513/1, 2011-2016, GBP5.87 million

4. Details of the impact

Bristol's COMPAVS and DEFGEN projects have led to significant economic and practical impacts in the aerospace, energy and other industries, both in the UK and internationally. The knowledge and numerical algorithms produced from this research have resulted in:

- The creation of a Bristol SME providing consultancy services for simulations and distortion predictions to over 40 companies in 14 countries;
- Reduced production time and increased quality of Vestas wind turbine component manufacturing for >2,500 turbines, now generating >8GW of power;
- Co-development and sale of new simulation software for aerospace, energy and automotive manufacturers worldwide, validating GBP millions of tooling components, with an updated version released in Summer 2020; and
- Achievement of right-first-time design for aerospace composite components with tight geometric tolerances for GKN, Airbus and Rolls-Royce products, including spars for 360 delivered A350s and 930 more on order.

Facilitated creation of an SME

LMAT ltd was founded in 2009 by Tomasz Garstka, who undertook his PhD studies within the COMPAVS project. LMAT was formed to provide consultancy services to composite component manufacturers in the aerospace, automotive, software and energy sectors, using novel numerical simulations and knowledge gained from the underpinning research [1-3] to predict composite manufacturing distortions for their clients. LMAT now has 4 employees and an annual turnover of GBP0.5 million [a].

Having established a reputation for high-quality work, a number of impacts were achieved in the REF 2021 eligibility period. "In its consultancy work LMAT has drawn upon and made use of the published research from the COMPAVS and DEFGEN projects to deliver technical solutions for composites manufacturing thus creating financial and competitive advantage for its customers." - LMAT, Managing Director [a].

Reduced production time and increased quality of wind turbine component manufacturing

Between 2014 and 2016, LMAT enabled VESTAS – one of the world's biggest wind turbine businesses – to increase production quality by reducing defect and scrap rate, thus leading to a reduction in production costs [a]. The objective of the work was to design an efficient way of processing wind turbine shells and spars. The experimental methodology, originally developed within the COMPAVS project [2], allowed LMAT to measure key material parameters, processing windows and cure cycle durations. Algorithms from the DEFGEN project [6] were used to predict the final thickness after consolidation and during cure of the part and reinforced adhesives. This work influenced the final choice of adhesive used in joining the two halves of a wind turbine blade, giving a longer processing window and allowing a fully closed bond-line to be achieved [a].

The technology deployed has been used on the manufacture and assembly of the [text removed for publication] wind turbine blades. [Text removed for publication]. As of 30 June 2020, a total of 2,118 of the [text removed for publication] wind turbines have been installed globally, with a generating capacity of 7,722MW. The [text removed for publication] turbine blade was first installed in [text removed for publication] and as of 30 June 2020, 414 of these turbines have been installed with a generating capacity of 1,724MW [c].

Figure 3. Vestas wind turbine installation in Finland - courtesy of Vestas Wind Systems A/S

Co-created new simulation product with US-based software provider

LMAT has worked closely with US-based commercial software provider, Ansys, to embed material behaviour models from the COMPAVS project [a] into their commercial-off-the-shelf (COTS) product for finite element simulation. This was launched as the Ansys Composites Cure Simulation (ACCS) module in May 2016 and is licensed as an additional package to the main Ansys software [d]. The ACCS products allow end users to simulate complex thermo-chemical reactions of epoxy resins as well as process-induced distortions in composite mouldings, "*optimizing your design while saving time and expense by reducing the product design cycle*." [d] Since 2016, the software has been "*sold to numerous companies in the aerospace, energy, health and automotive sectors around the globe for use in their product development cycles*" [e].

"*LMAT...developed [Ansys ACCS] in response to the growing market demand for a reliable simulation platform to support manufacturing and tooling engineers throughout the process design cycle. The platform has been comprehensively validated and subsequently used to compensate millions of pounds worth of rib, spar and wing-skin tools across the European aerospace and wind energy industries, where previously the only method of achieving parts of sufficiently high tolerance to meet strict aerospace assembly rules was to re-machine finished tooling after molding the first part*." [d] The success of the ACCS module has led to a new release in 2020 [f] that now includes cure simulation algorithms from [5] [a].

Achieved right-first-time design in aerospace manufacture

Between 2014 and 2017, LMAT played a significant role in supporting GKN Aerospace in the design of the Airbus A350 XWB wing trailing edge spar tooling. The aircraft is Airbus' first to have both a carbon-fibre wing and fuselage, with GKN Aerospace subcontracted to design and manufacture the composite spars. LMAT's involvement in the design process and their use of the ACCS software [e] led to reduced distortion and achieved a right-first-time design [a]. First, LMAT used the experimental measurement methodology developed at UoB to characterise materials for use on the A350 aircraft. LMAT then used modified numerical algorithms from the

COMPAVS and DEFGEN projects to design tooling surfaces and Automated Fibre Placement (AFP) mandrels for the -900 and -1000 series aircraft trailing edge spars. LMAT's approach allowed GKN to save millions of pounds compared to the alternative trial and error approach that would have required several attempts as well as recutting and corrective work on the spar mould and mandrel, which typically cost [text removed for publication]. The work by LMAT also reduced the development cycle for a spar mould/mandrel tool set by at least six months [a].

The spars made using LMAT-designed tooling are now used on both the A350-900 and A350-1000 aircrafts. The A350-900 entered service on the 15th January 2015, and the A350-1000 on the 24th February 2018, both with launch operator Qatar Airways. As of March 2020, there were 760 orders and 320 deliveries of the -900 series and 170 orders and 41 deliveries of the -1000 series [g].

The UoB research described in section 2 has also been successfully implemented in the manufacturing processes of other aerospace components between 2014 and 2018 by Triumph Aerospace, to manufacture compensated mould tooling surfaces. Notably the Airbus A350 [text removed for publication], for which 100s of parts have been produced to date [a,h] and also [text removed for publication] for Rolls-Royce aeroengines, that require a high degree of precision in design and manufacture to meet strict tolerances and overcome distortion caused to assembly during the bond cure processes. This has included over 700 parts for the [text removed for publication] [i]. "*Our suppliers must conform to our rigorous quality standards for aero-engine components. These parts produced by Triumph were all accepted as they delivered the tight geometric tolerances that are essential for the accurate assembly of composite aerospace components*." Rolls-Royce - Manufacturing Engineering Executive, Compressors [i]. More recently 680 parts were manufactured for the [text removed for publication] business jet engine [a,h]. "*The most recent engagement which delivered compensated tool surface geometries, accounting for cure distortions on multiple material systems with varying properties, has enabled Triumph to deliver a number of fan-case liners to Rolls-Royce who have commended the product quality and ease of assembly*." Triumph Aerospace Structures - NPI Lead Program Engineer [h].

New sectors

The success of LMAT's technology, derived from research at the University of Bristol has been notable, as demonstrated above. It is now being deployed into new sectors, such as automated 3D printing of composite components, with 9T labs of Switzerland. "*With the help of LMAT, we can automate manual processes that may take days and achieve according time savings*" 9T Labs -COO [j].

5. Sources to corroborate the impact

[a] LMAT Ltd – Corroborating statement (2020), Managing Director
[b] Vestas – Company news (December 2015), *Vestas receives 117 MW order in Finland* [Accessed 12/5/20]
[c] Vestas' track record by turbine type: https://www.vestas.com/en/products/track_record#!results-by-turbine-type [Accessed 30/9/20]
[d] Ansys white paper, *Ansys Composite Cure Simulation* [Accessed 28/5/20]
[e] Ansys – Corroborating statement (2020), Lead R&D Engineer
[f] Ansys – Capabilities brochure (2020) [Accessed 30/9/20]
[g] Airbus publications (2020): https://www.airbus.com/content/dam/corporate-topics/publications/o&d/ODs-March-2020-Airbus-Commercial-Aircraft.xlsx [Accessed 12/5/20]
[h] Triumph Aerospace Structure – Corroborating statement (2020), NPI Lead Program Engineer
[i] Rolls-Royce – Corroborating statement (2020), Manufacturing Engineering Executive Compressors
[j] 9T Labs – Corroborating statement (2020), COO