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ADVANCED COMPOSITES COLLABORATION FOR INNOVATION & SCIENCE

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The Composites Centre

for research, modelling, testing and training in advanced composites

High Performance Ductile Composite Technologies (HiPerDuCT) EPSRC Programme Grant

Final Report [EP/I014322/1]

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HiPerDuCT Programme Grant Final Report [EP/I014322/1]

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This report summarises the research carried out under the EPSRC Programme Grant on High Performance Ductile Composites Technology between 2011 and 2018. A large collaboration between Bristol University and Imperial College investigated different ways of introducing ductility and pseudo-ductility into high performance composites. The programme initiated a new field of research and demonstrated that it is possible to create composites that fail more gradually.

1. Introduction

1.1 Background

Composites have become established as the materials of choice due to their high mechanical performance and continue to expand rapidly into new markets and applications. Conventional polymer matrix composites offer high strength and stiffness, low weight, and low susceptibility to fatigue and corrosion. Properties can be tailored to particular applications and additional functionality can be incorporated, e.g. for sensing, self-healing, morphing or energy storage. Composites are increasingly being used in aerospace and other applications, such as wind turbine blades, sporting goods and civil engineering. Despite this progress, a fundamental limitation of current composites is their inherent brittleness. Failure is usually sudden and catastrophic, with little warning or residual load carrying capacity. Structures that satisfy a visual inspection can fail suddenly at loads much lower than expected, so complex maintenance protocols are required, and significantly greater safety margins than for other materials.

1.2 Creativity in Composites Engineering

A call for programme grant proposals on ‘Creativity in Composites Engineering’ was issued by EPSRC in 2010. The aim of this call was to address longer-term challenges to help fully realise the potential of composite materials. Both Bristol University and Imperial College independently identified a key limitation of conventional composites as their inherent lack of ductility. A natural partnership emerged and it was agreed that solving this problem, whilst being a highly ambitious undertaking, would have the most significant impact on the usability of composites materials in a range of applications.

1.3 Aim

The aim of this programme was to realise a new generation of high performance composites that overcome the key limitation of conventional composites: their inherent lack of ductility. We sought to design, manufacture and evaluate a range of composite systems with a ductile or pseudo-ductile response, while maintaining strength and stiffness. The ability to yield and recover, be notch insensitive, exhibit high work of fracture, and fail in a benign manner, would offer a step change in damage tolerance, increasing the scope of applications and enabling new processing techniques.

2. Programme

2.1 Introduction

The programme on High Performance Ductile Composites Technology (HiPerDuCT) ran from July 2011 until June 2018. Prof. Michael Wisnom was the Principal Investigator and chair of the Management Team, which consisted of all the co-Investigators: Prof. Alexander Bismarck, Prof. Paul Robinson and Prof. Milo Shaffer from Imperial, and Prof. Kevin Potter, Prof. Ian Bond and Prof. Paul Weaver at Bristol. Sadly Dr Joachim Steinke from Imperial died in January 2013. Soraia Pimenta, a researcher on the programme obtained an academic staff position at Imperial in September 2013 and joined the management team. Prof. Ian Hamerton also joined following his appointment at Bristol in 2016.

2.2 Structure of Programme

Fig. 1 shows the overall structure of the programme, which was split into two domains: (1) *Architecture* and (2) *Constituents*. These were sub-divided into inter-related themes addressing three fundamental mechanisms to create ductility: by reorientation of fibres to take advantage of excess length (*Theme A*); by slip and fracture between aligned fibres (*Theme B*); and by means of ductile constituents (*Theme C*). This approach allowed the challenge to be tackled at length scales from molecular to structural.

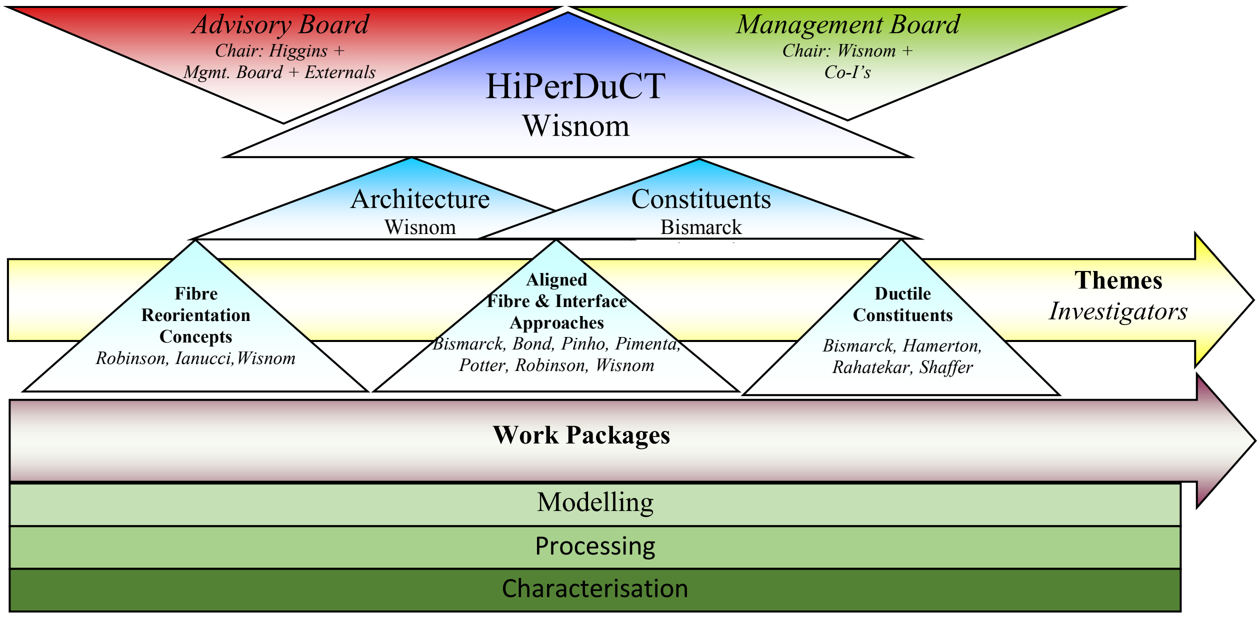

Fig. 1. Structure of HiPerDuCT Programme

2.3 Management

The Management Team met monthly with the purpose of reviewing milestones and deliverables; planned publications; Intellectual Property; programme finances and allocation of funding. In addition, each work package was periodically reviewed to decide whether it should carry on or not.

An advisory board met annually to review the programme and provide feedback and comments on future direction. This was chaired by Prof. Dame Julia Higgins, FRS, FREng (Imperial College, and former Chair of EPSRC) and comprised: Prof. Anthony Bunsell (Ecole des Mines); Prof. Tsu-Wei Chou (University of Delaware); Prof. Ignace Verpoest (KU Leuven); Prof. Karl Schulte (TU Hamburg-Harburg);

Dr David Attwood, Brett Hemingway, Dr Amir Rezai (BAE Systems); Dr Rob Backhouse, Adam Bishop (Rolls-Royce); Prof. Paul Curtis (Dstl); Dr Alex Baidak, Dr David Tilbrook (Hexcel); and Dr Dan Kells, Dr Dan Thompson (NCC). Additional industry review meetings were held in between advisory board meetings.

2.4 Collaborators

The industrial partners in HiPerDuCT were: BAE Systems, Hexcel Composites, and Rolls-Royce. Collaborations were developed within the wider composites communities at both Bristol and Imperial, with a number of activities involving academics who were not investigators on the grant. Additional external partnerships were established, for example with Manchester University on textile composites, Exeter University on cellulose fibre precursors, Strathclyde University on fatigue sensors, Dundee University on laser modification of fibres, Cambridge University on carbon nanotube fibres, KU Leuven on hybrid composites, IMDEA in Madrid on high resolution micro strain measurements, BAM in Berlin on interfacial characterisation of modified fibres, and BME in Budapest on environmental characterisation of hybrids.

3. Highlights of the Programme

The programme investigated a number of different potential mechanisms for creating more gradual failure and successfully demonstrated pseudo-ductility in all of them. A key measure used to assess progress was pseudo-ductile strain, defined as the difference between the final failure strain, and the elastic strain at the same stress.

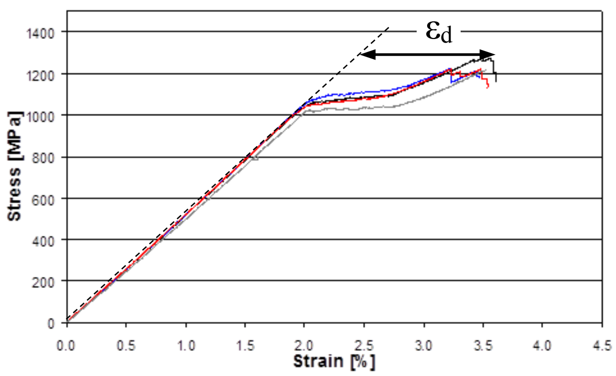

Fig. 2 Pseudo-ductile strain ε_d in glass/carbon thin ply hybrid

- Thin-ply carbon angle-ply composites have been shown to allow fibre rotation under load producing 1.2% pseudo-ductile strain without delaminating and a maximum stress of 950 MPa. Deformation was shown to be reversible, indicating that this is true ductility (WP A1).
- Wavy ply sandwich composites have been created with up to 9% strain at the structural level and high energy absorption (WP A7, patent submitted).
- Co-mingling of different fibre types has been achieved, giving a more gradual failure with 14% increase in maximum strain (WP B1).

- A new mechanism of ply fragmentation has been demonstrated in thin ply hybrids, producing a non-linear stress-strain response with a plateau and pseudo-ductile strains of up to 2.7%. Quasi-isotropic laminates have been produced demonstrating notch insensitivity. Fatigue performance is good. Pseudo-ductility has also been demonstrated under compression, bending, and bearing loads (WP B3).
- Ply fragmentation has been combined with angle plies to create all-carbon laminates with a strength of 700 MPa and pseudo-ductile strain of 2.2%. A tubular tension member has successfully demonstrated pseudo-ductility whilst carrying 89kN.
- Glass/carbon hybrids produce a striped pattern that can be used as a simple static or fatigue overload sensor (WP B3).
- Hybrid specimens can avoid grip failures, enabling improved unidirectional tests and giving new understanding of the hybrid effect, specimen size effects, and failure criteria (WP B3).
- Model systems of discontinuous prepreg have shown the potential for additional strain via slip at the interfaces (WP B4).
- A novel manufacturing process has been developed allowing high volume fraction highly aligned discontinuous fibre composites to be produced (WP B5.1, patent submitted). These have shown record modulus and strength for single materials, approaching those of continuous fibre composites. Pseudo-ductile strain of 1.1% has been demonstrated, with the ability to achieve novel architectures with different fibre types, lengths and distributions. Multiaxial composites have been produced which can deform during manufacture to produce complex shapes. High performance composites have been created from recycled fibres.
- Good progress has been made towards creating ductile nanotube fibres that show high initial modulus and high strains to failure (WP C2.1). Tensile strength of 1.4 GPa has been achieved with a strain to failure of 12.7%, with much higher strains at reduced strength.
- A new class of nacre mimic has been prepared (WP C2.2). Coated fibres showed reduced local stress concentrations arising from fibre breaks and increased slippage.
- Comprehensive modelling of the deformation and damage mechanisms has been undertaken, giving a good understanding of the factors controlling performance, for example the effect of constituents, variability and defects on the behaviour of discontinuous hybrids (WP B8).
- Over 50 journal papers and more than 60 conference papers have been published.

4. Summary of Work Packages

Table 1 below summarises the work packages undertaken. In bold are the completed WPs resulting in publications for which reports with details are given in the appendix. The table also lists a number of initial feasibility studies, or projects which were not continued. Missing numbers are due to projects that were not in the end undertaken, or were reorganised into other WPs.

	Work Package (Lead)	Key Challenge
Theme A – Fibre Reorientation Concepts	**A1 Angle plies (Wisnom)**	To create optimised angle ply laminates achieving 'ductility' through fibre rotation and matched matrix response.
	A5 Microbraided ropes (Iannucci, Robinson)	To investigate micro-braided hybrid fibre architectures and to assess the potential for creating pseudo-ductile response of resulting composites.
	A7 Wavy ply sandwich (Robinson)	To demonstrate large deformations in a wavy-ply sandwich with composite skins and crushable core.
	A8 Wavy ply discontinuities (Robinson)	To evaluate the potential of in-plane wavy ply composites for a more ductile behaviour.
	A9 Ductile micro-braided helical structures (Weaver)	To establish the feasibility of creating micro-braided structures displaying favourable load-extension characteristics.
	A10 Friction mechanisms (Robinson)	To use of friction mechanisms in order to achieve pseudo-ductile behaviour while keeping high modulus and strength.
	A11 Triaxial braided composites (Pinho)	To explore the potential of triaxial braided composites for pseudo-ductility.
	A12 Auxetic Architectured UD hybrid composites (Scarpa)	To investigate auxetic slitting patterns to increase strain to failure of UD hybrid composites.
	A13 Hierarchical perforations for enhanced ductility (Allegri)	To use controlled defects (in-plane fibre waviness and resin rich areas) to promote pseudo ductility.
	A14 Multi-scale multi-fibre hybridisation (Wisnom, Potluri - Manchester)	To achieve pseudo-ductility via micro-wrapped/ spread tows in braided and 3D woven hybrid architectures.
Theme B – Aligned Fibre and Interface Approaches	**B1 Hybrids – intermingled fibre types (Bismarck)**	To manufacture hybrid composites using a range of fibre types and optimise to maximise pseudo-ductile composite response.
	B2 Hybrids – modulated fibre properties (Bond, Bismarck)	To develop modified high strength, high stiffness fibres with properties modulated along the length and investigate their potential to contribute to pseudo-ductility.
	B3 Hybrids - Thin prepreg (Wisnom)	To optimize and exploit the pseudo-ductility of thin-ply hybrid composites under a range of different loading conditions
	B4 Discontinuous pre-preg (Bismarck)	To achieve pseudo-ductility by introducing toughened interleaves in unidirectional composites with pre-defined cuts.
	B5.1 Discontinuous fibre manufacturing (Potter)	To develop novel manufacturing methods for aligned short fibre composites for high performance ductile response.
	B5.2 Liquid crystalline manufacturing (Bismarck)	To create a liquid crystalline suspension of short carbon fibres at a relatively high concentration.
	B5.3 Thermoplastic extrusion manufacturing (Bismarck)	To produce aligned short fibre thermoplastic composites with high fibre volume fraction and low void content via twin screw extrusion of UD composite tapes.
	B5.5 Laser patterned discontinuous fibres (Bismarck)	To create discontinuous prepreg with controlled patterns using a laser.
	B5.8 Laser modified fibres (Bismarck)	To exploit pre-weakened and modified fibre shapes to create pseudo-ductility.
	B6 Hierarchical bundle composites (Pimenta)	To create small sub-bundle composites and validate the model for hierarchical ductile composites.
	B7 Interlaminar and ply weakening (Robinson)	To exploit interlaminar and ply weakening to generate pseudo-ductility.
	B8 Discontinuous composites across the scales (Pimenta)	To use modelling to optimise the pseudo-ductile response of discontinuous composites.

Theme C – Ductile Constituents	**C2.1 High performance ductile fibres (Shaffer)**	To fabricate high-performance ductile fibres based on internal strain hardening between nanostructured elements.
	C2.2 Nacre-inspired interphase (Shaffer)	To coat fibres with nanoplatelet layers that can shield fibre breaks and lead to a strain hardening interface.
	C3 High Performance Ductile Matrices (Shaffer)	To develop new high strength, high stiffness polymeric matrices with large failure strain and low creep.
	C4 Carbon Nanotube Fibres and Sheets (Rahatekar)	To use high performance carbon nanotube fibres as potential ductile constituents for composite reinforcement and control of crack propagation
	C5 Realising the Potential of Carbon Fibre Composites in Compression (Wisnom)	To suppress the shear instability or control it to achieve ductile compression behaviour of carbon composites.
	C6 Optimised Matrices (Hamerton)	To tailor composites with matrices optimised to meet the requirements in other WPs.
	C7 Ductile Superlattice Nanoparticle Matrices (Shaffer)	To create ductility via dislocation-based deformation in an ordered nanoparticle supercrystal matrix.
	C8 Carbonised Cellulose Fibres (Rahatekar – Cranfield, Eichhorn-Exeter)	To create higher strain fibres by controlled carbonisation of regenerated cellulose and cellulose nanocomposite precursors.

Table 1. Summary of Work Packages

5. Added Value and Impact

5.1 Added Value

A key success has been the creation of a tightly integrated research team working both across work packages and institutions to provide a coherent and well-coordinated programme, with monthly meetings of the whole team held alternately at Bristol and Imperial throughout the programme.

A number of research workshops and brainstorming sessions were held to explore new and creative approaches to tackling the challenges of creating ductile composites. These workshops had the added benefit of bringing in other academics with additional expertise to explore how their research ideas could contribute to the programme and seed corn funding was provided to initiate a number of new projects.

In addition to the research directly funded under HiPerDuCT, twelve PhD projects were aligned with the programme, listed in Table 2.

Jonathan Fuller	Pseudo-ductility of thin ply angle-ply laminates	Bristol CDT, 2015
Hele Diao	Carbon fibre reinforced polymer composites with enhanced ductility	Imperial PhD, 2015
Henry Maples	Shape changing composites	Imperial PhD, 2016
Stephano del Rosso	Micro-braided composites	Imperial PhD, 2016
James Trevarthen	Towards CNT Fibre/Polymer Composites	Bristol CDT, 2016
Francois de Luca	Fibre-Reinforced Composites with Nacre-Inspired Interphase: A Route Towards High Performance Toughened Hierarchical Composites	Imperial PhD, 2018

Xun Wu	Behaviour of pseudo-ductile thin-ply angle-ply laminates under different loading conditions	Bristol CDT
Putu Suwarta	Pseudo-ductility of Unidirectional Thin Ply Hybrid Composites	Bristol PhD
Tamas Rev	Exploiting thin-ply hybrids to establish failure criteria under multi-axial loading	Bristol CDT
Jakub Rycerz	Realising the potential of carbon fibre composites in compression	Bristol CDT
James Finley	Developing ductile composite materials across a range of strain-rates and scales	Imperial PhD
Jingjing Sun	Pseudo-ductile composites with weakened plies	Imperial PhD

Table 2. PhD Projects Aligned with HiPerDuCT

5.2 Contributions to and beyond the discipline

Many contributions have been made to important topics in composites research such as failure mechanisms, novel modelling approaches, hybrids, short-fibre composites, interfacial characteristics, composites with controllable stiffness, bi-continuous aerogel matrices and nanotube fibres. In addition the thrust of the programme to create ductile composites has stimulated interest in this new direction, which is quite distinct from other current research, opening up a completely new research area. We organised dedicated sessions on the theme of ductile and pseudo-ductile composites at the International and European Conferences on Composite Materials, the leading conferences in the field. Sessions at ICCM21 in Copenhagen in 2015, ECCM16 in Munich in 2016, ICCM22 in Xian in 2017 and ECCM17 in Athens in 2018 have all been well attended and created significant interest.

5.3 Dissemination and Impact

Dissemination of results was mainly through publication of journal papers and presentations at major international conferences such as ICCM and ECCM. A number of invited presentations were given, including a plenary by Prof. Michael Wisnom at the ICCM21 conference in Xian in August 2017. A website www.hiperduct.ac.uk, provides information on the programme, including publications.

Two industry and academic engagement meetings were held at the National Composites Centre in 2015 and 2017 to share programme outputs, attract new partners and to get feedback on industry requirements.

A new £1.3M EPSRC project on “High Performance Discontinuous Fibre Composites: A Sustainable Route to the Next Generation of Composites” is taking forward this element of the programme, scaling up the HiPerDiF process and applying it to a range of applications, led by Prof. Ian Hamerton.

An impact acceleration project was also funded on “Application of the HiPerDiF (High Performance Discontinuous Fibres) manufacturing method for Quality Control of reclaimed carbon fibres in recycled composite materials” in collaboration with ELG Carbon Fibre Ltd, which demonstrated that the method could be successfully applied to the property measurement and quality control of reclaimed carbon fibres and recycled composites.

A second impact acceleration project was also funded on “Hybrid composite strain overload sensor concept in real-life applications – Market search and industrial partnership for exploitation of the invention”. This identified a number of potential applications for the technology, and companies which could potentially benefit. Further activity is being pursued directly with some of these companies, and a Technology Pull-Through project has been funded by the National Composites Centre to investigate the repeatability and environmental stability of the sensors, and look at scale-up and applications.

Further work is also being pursued on other potential applications, for example the use of hybrid composites for resisting impact in aero-engine components in collaboration with Rolls-Royce.

Another key impact is that six researchers including all the initial team members moved on to academic appointments and remained involved in HiPerDuCT in their new positions: Dr. Jonny Blaker, University of Manchester; Dr. Soraia Pimenta, Imperial College; Dr. Gergely Czel, Budapest University of Technology and Economics; Dr. HaNa Yu, Bath University; Dr. Meisam Jalalvand, University of Strathclyde; Dr. Mohammad Fotouhi, University of the West of England.

5.4 Patents

Six patent applications were filed during the course of the programme, listed in Table 2.

Reference	Title
GB1306762.4	Method and apparatus for aligning discontinuous fibres
GB1405824.2	Wavy Sandwich Structural composite material
PCT/GB2013/050826	Composite Material Suitable for a Morphing Skin
P120511GB	Visual Strain Sensor
1700641.8	Fatigue sensor
1621494.2	Nacre-like decorated fibre for hierarchical ductile composite

Table 3. HiPerDuCT Related Patent Applications

6. Conclusion

This programme has shown that it is indeed possible to create high performance composites that fail gradually with ductile or pseudo-ductile response and notch insensitivity. A strong collaboration has been established between Bristol and Imperial, and a wide range of novel approaches investigated. A number of new ways of creating additional strain have been successfully demonstrated via fibre rotation, in-situ fragmentation, fibre ductility and slip in continuous and discontinuous composites. A whole new field of research has been initiated, with a large body of work published in top journals and conferences. This work is being continued through new grants, in conjunction with industry and the NCC, and through the research of the team of outstanding researchers who now have their own academic positions.