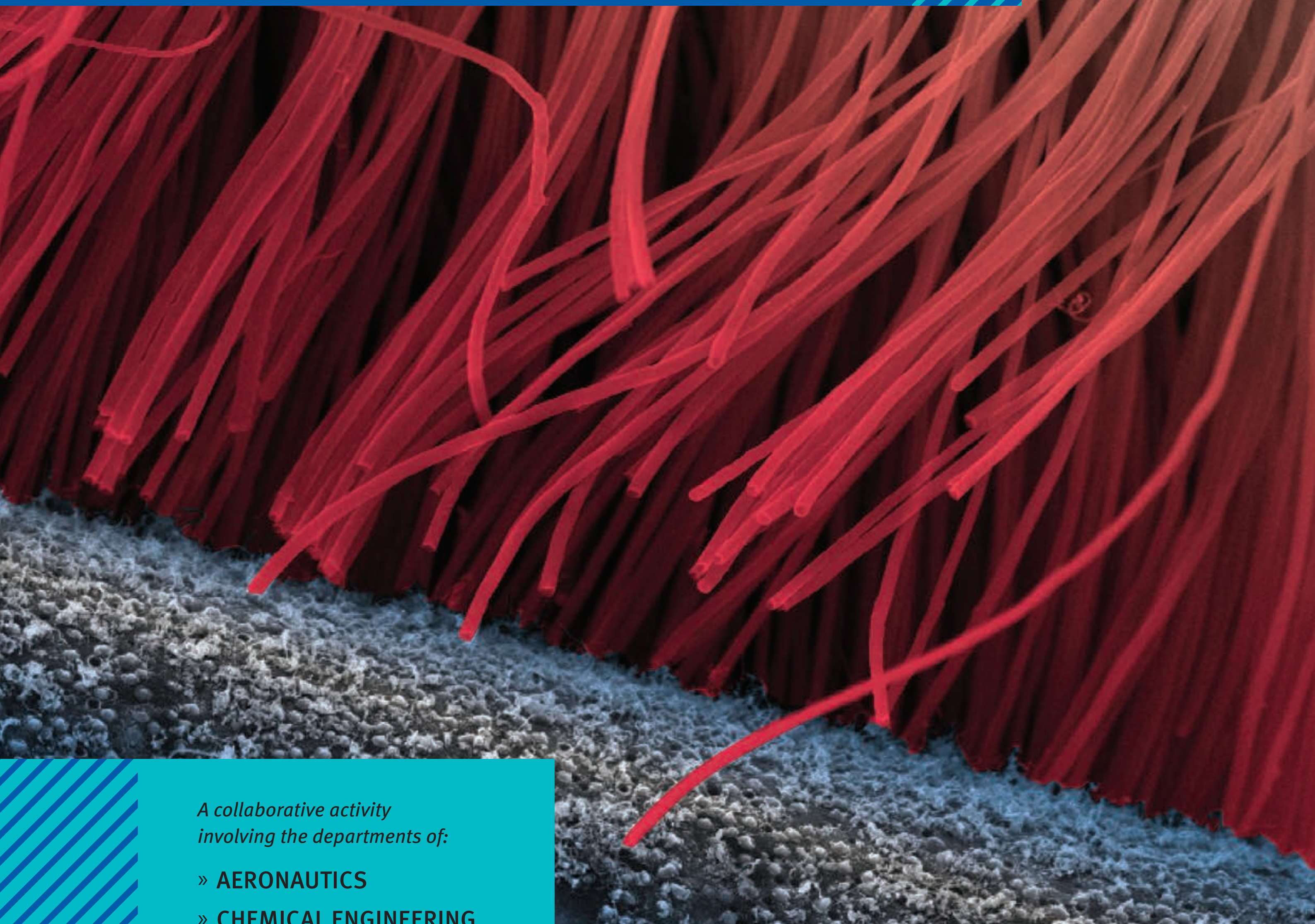
Imperial College London

The Composites Centre

FOR RESEARCH, MODELLING, TESTING AND TRAINING IN ADVANCED COMPOSITES



A collaborative activity involving the departments of:

- AERONAUTICS
- CHEMICAL ENGINEERING
- CHEMISTRY
- CIVIL ENGINEERING
- DYSON SCHOOL OF DESIGN ENGINEERING
- MATERIALS
- MECHANICAL ENGINEERING

Research, Facilities and Expertise

Annual Report 2018/19

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On the cover: Carbon nanotubes grafted onto a structural fibre to improve interfacial performance of fibre reinforced composites.

Introduction

It is with considerable pride that I introduce The Composites Centre at Imperial College London.

WELCOME TO THE COMPOSITES CENTRE REPORT, which provides comprehensive details of our active composite research, experts and the associated facilities across Imperial College London. This is the first time since 2008 that we have collated and presented such an overview of our Composites research, so we anticipate that this document will provide a valuable insight into the exciting and innovative work we are doing at Imperial College London.

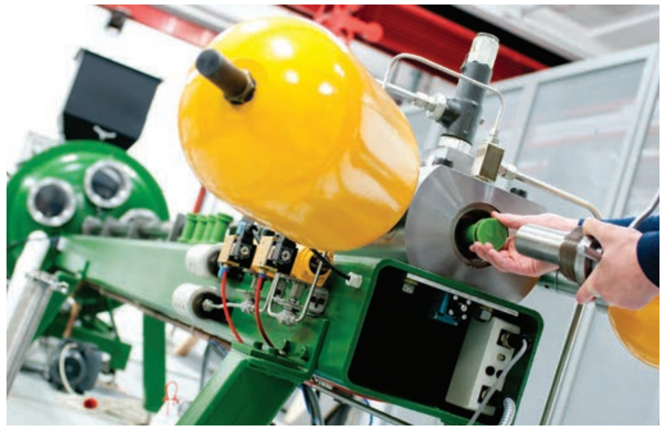
Our research portfolio is grouped into six themes:
» Synthesis of new and multifunctional materials;
» Composite design, life cycle analysis and recycling;
» Composite manufacture and repair;
» Composite analysis, modelling and prediction;
» Experimental mechanics; and
» Composite inspection and characterisation.

Detailed information on the active research topics within each of these themes is briefly given within, but to demonstrate the breadth and range of maturities (i.e. TRLs) of our research, we have also highlighted some selected activities in depth. We introduce the academic and research staff affiliated with the Composites Centre, and then detail the Facilities we have for manufacture, characterisation and testing of composites. Finally, we have provided details of the mechanisms by which you can interact and collaborate with us.

We hope this report will provide a valuable and informative snapshot of the work we are currently doing. Finally, if you wish to receive further information on any of the projects, experts or facilities listed in this report, you are most welcome to contact either me or the staff directly involved.

PROFESSOR EMILE S. GREENHALGH
Director of the Composites MSc and
Head of the Composites Centre

▲ *We engineer new composites in our Materials Synthesis laboratory.*



▲ *Loading the gas gun to characterise high rate performance of composites.*

▼ *We are investigating the effect of compressive preload on impact resistance of composite structures using our unique impact under load capability.*

About the Centre

Over the last thirty five years the Composites Centre has provided a focus for the entire composites expertise across seven Departments in the College: Aeronautics, Chemical Engineering, Chemistry, Civil Engineering, Dyson Design School, Materials and Mechanical Engineering. Over the last four decades we have gained a track record in delivering world-leading and ground-breaking research over a huge spectrum of different composite constituents, architectures, manufacturing routes, characterisation and modelling techniques and design for final applications. Given that Composites is recognised as a critical technology for the future prosperity of the UK, and UK-based composite product production is anticipated to grow by more than fivefold by 2030*, the expertise that resides in the Composites Centre is well positioned to collaborate with industry and research funders such as yourselves.

We have about thirty academics with an established reputation in innovating and undertaking research and industrial development in composites. Based on the 2014 Research Excellence Framework (REF), we have the most world-leading composite academics in any UK University. A team of highly skilled and experienced technicians maintains our comprehensive composite facilities. Finally, complimentary to the research is the training we offer, both bespoke short courses and the only established MSc in Composites in the UK, which was started in 1988.

As conveyed herewith in, we take great pride in the unique breadth and quality of the Composites research we undertake, and strive to inspire innovation in this exciting and growing field. In particular, we have trail blazed the synthesis of novel constituents and their resulting composites. We lead development of new modelling methods and design philosophies for composites and have developed innovative methods to characterise composites, particularly regarding damage and failure processes.

** Composite Leadership Forum, www.compositesleadershipforum.com.*

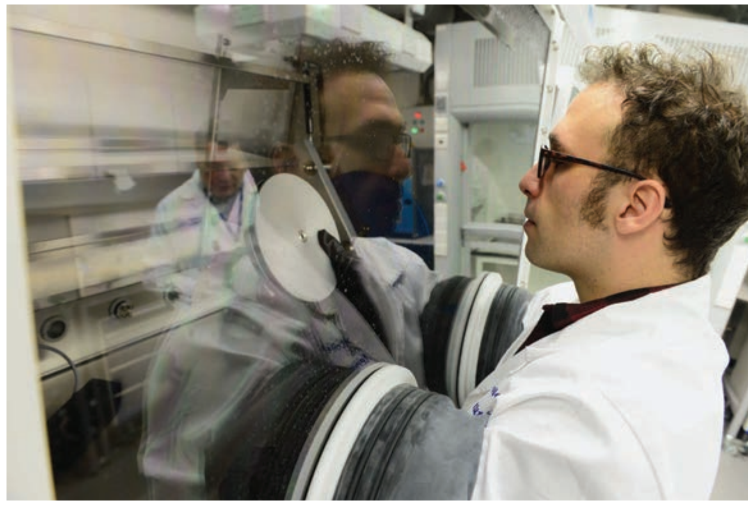
» **Our Vision** is to be the world leading resource for composite knowledge, research and training, ranging from conception of novel and new composites and architectures, to the design, testing and analysis of full-scale composite components in support of industry.

MISSION

» **To create, utilise and disseminate knowledge in the field of composites to meet the needs of the industry and to contribute to the continued success and ambitions of our academics.**

» **To provide potential collaborators and stakeholders with comprehensive visibility of, and access to, all the composite expertise and knowledge across Imperial College London, and hence facilitate new and nurture existing collaborations.**

» **To educate and train engineers and scientists in composites.**



▲ *We have glove box facilities to assemble multifunctional structural power materials in a moisture and oxygen free environment.*

TOP 10
of world universities

8TH IN THE WORLD
4TH IN EUROPE
QS World University Rankings 2019

3RD IN EUROPE
8TH IN WORLD
Times Higher Education (THE) World University Rankings 2018

Imperial College London is a one-of-a-kind institution in the UK, focusing solely on science, engineering, medicine and business.

Research Environment and Impact

RESEARCH EXCELLENCE FRAMEWORK (REF–2014)

1ST

The REF's impact measure ranks Imperial's research the highest of any major university.

Moreover, eight of Imperial's 14 REF-assessed research areas are top or joint-top for "outstanding" or "very considerable" impact.

4*

Overall, Imperial comes fourth out of major UK universities for 4* or "world-leading" research.

Individual Departments affiliated with the Centre:

3rd Civil Engineering
3rd Materials
4th Aeronautics
4th Chemical Engineering
4th Mechanical Engineering
7th Chemistry

91%

91% of Imperial research is classed as "world-leading" or "internationally excellent" — the highest proportion of any major university.

Top

Imperial was ranked top or joint-top for providing an environment conducive to producing 4* "world-leading" or 3* "internationally excellent" research in all of the Units of Assessment to which it made submissions.

The Complete University Guide 2019

UK University League Table Ranking

NO. 2	AERONAUTICAL & MANUFACTURING ENGINEERING
NO. 3	CHEMICAL ENGINEERING
NO. 3	GENERAL ENGINEERING
NO. 3	MECHANICAL ENGINEERING
NO. 3	MATERIALS TECHNOLOGY
NO. 4	CIVIL ENGINEERING
NO. 6	CHEMISTRY

GOLD

TEACHING EXCELLENCE FRAMEWORK (TEF)

Awarded to institutions that consistently deliver outstanding teaching, learning and outcomes for their students

0.92 / 1.00

RESEARCH INTENSITY

A measure of the proportion of staff involved in high-quality research in the university.

The Times and Sunday Times Good University Guide 2018

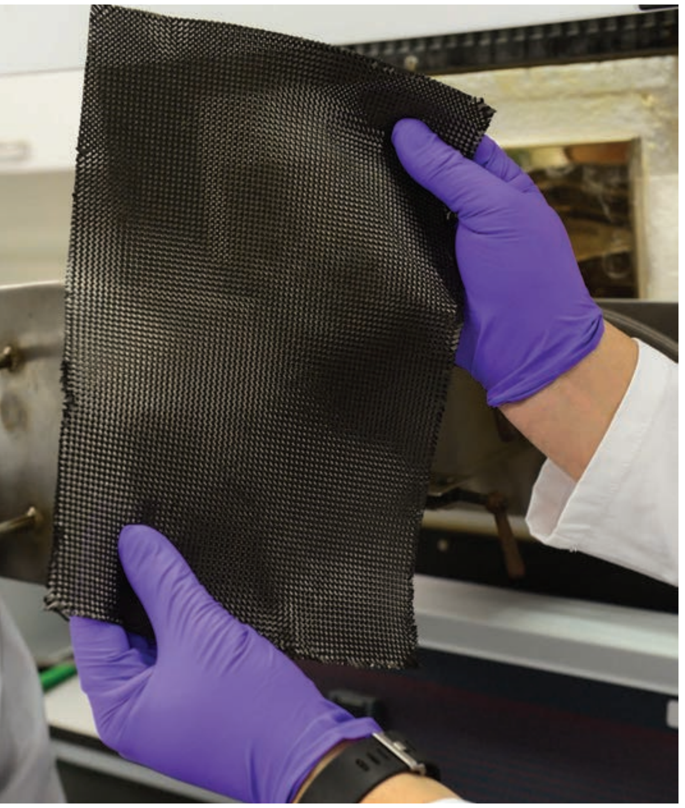
4th IN THE UK

The Guardian University Guide 2019

7th IN THE UK

Research highlights

Our research covers a very broad spectrum of topics, with a strong partnership between prediction and experiment, as well as strong links with industry.



▲ *Lamina being prepared for carbon aerogel infusion.*

◀ *Prof Greenhalgh demonstrates a structural power component.*

01 Multifunctional Structural Supercapacitors

Academic lead • PROF E.S. GREENHALGH

We have established an alternative concept to smart structures, in which the constituents themselves are multifunctional, acting in synergy to give truly multifunctional materials which inherently perform two (or more) disparate functions simultaneously. This step beyond smart structures has attracted enormous academic, public and industrial interest. In particular, we have demonstrated structural power composites — structural composites which have the ability to store/deliver electrical energy. These materials offer considerable performance advantages whilst presenting fascinating opportunities for innovative design. The potential for weight and volume savings by adopting intrinsically multifunctional materials are compelling, but the research challenges are immense.

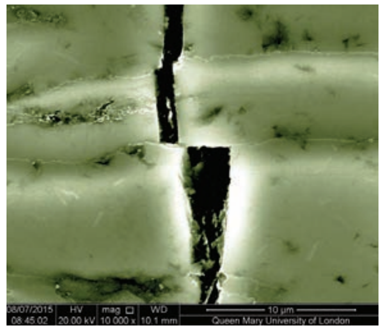
We have an active group and large portfolio of research to investigate and develop these materials. Firstly, under EPSRC funding, we have the project Beyond Structural in which we are investigating the fundamental science that underpins the electrical and mechanical performance of our multifunctional materials. In parallel, we are developing predictive models of both the mechanical and electrical performance of these materials, with the aspiration to meld them to deliver a multifunctional predictive tool. Again under EPSRC funding (Composite Manufacturing Hub), we are investigating the manufacturing and design challenges associated with using these structural power materials. Under USAF funding we are investigating the interactions between the electrical and mechanical performance of these materials, and importantly, characterise what happens when these materials are impacted, damaged or penetrated whilst electrically charged. Finally, we have funding from H2020 (SORCERER) to demonstrate this technology. Structural power materials are an exciting technology which addresses the key areas of energy storage and light weighting, and we anticipate they will herald a completely different approach to using structural materials in the future.

02 Graphene-based composites

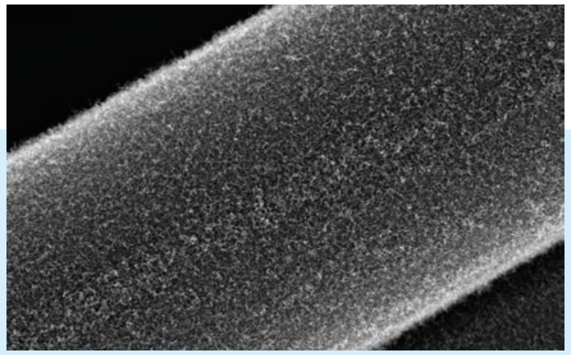
Academic lead • PROF E. SAIZ

We are developing novel approaches for the fabrication of graphene-ceramic and graphene-polymer composites. These approaches combine techniques such as 3D printing, freeze casting, pre-ceramic polymers and spark plasma sintering. The goal is to take advantage of the 2D nature of graphene in order to design and create a highly interconnected microscopic network of thin, electrically conductive interfaces inside a ceramic or polymer matrix. This network directs crack propagation and promotes stable crack growth, thus increasing fracture resistance. It also provides functional properties such as electrical and thermal conductivity. It can trigger Joule heating and be used to follow the formation and propagation of cracks in situ. The combination of self-monitoring and high-fracture resistance will be the basis for the development of intelligent materials able to avoid catastrophic failure in service.

This work is funded by EPSRC, initially through the grant Graphene 3D Networks and now through MAPP (Future Manufacturing Hub in Manufacture using Advanced Powder Processes). We are also investigating an extension to the technology towards the fabrication of self-healing and self-shaping composites funded by DARPA and ONRG.



▲ *Fracture in a graphene-based ceramic composite.*



▲ *CNTs grafted onto structural fibres.*

03 Nano and hierarchical composites

Academic lead • PROF M. SHAFFER

Certain nanomaterials, particularly carbon nanotubes (CNTs) and graphenes, offer the potential for fundamental improvements in mechanical performance and associated weight reduction. Individual nanocarbons have been shown to have a significantly higher strength than other known materials, combined with excellent stiffness, high lateral flexibility, high aspect ratio, and low weight. In addition, they have good electrical and thermal conductivities, and interesting optoelectronic characteristics, all relevant to (multi) functional performance. There is a large body of work on nanocomposites often showing useful improvements but at a relatively modest scale, based on the introduction of only very low loading fractions. On the other hand, assemblies based on pure CNTs, high loading contents and macro pre-forms have demonstrated significant promise, providing reports of the toughest/strongest fibres. At Imperial we have developed unique methods to process undamaged nanomaterials, whilst modifying the interfacial chemistry, to develop a new generation of high strength, high ductility structural fibres. In the nearer term, nanocarbons may have the biggest impact by enhancing the performance of existing state-of-the-art carbon fibre composites, particularly by addressing critical matrix-dominated failures, for example related to compression and delamination. Imperial College London has developed new, continuous/scalable processing methods that deliver hierarchical composites with high loading fractions of carbon nanomaterials, either within the matrix or grafted at the interface of conventional structural fibres.

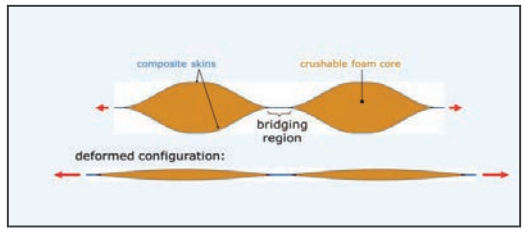
04 Ductile composites

Academic lead • PROF P. ROBINSON

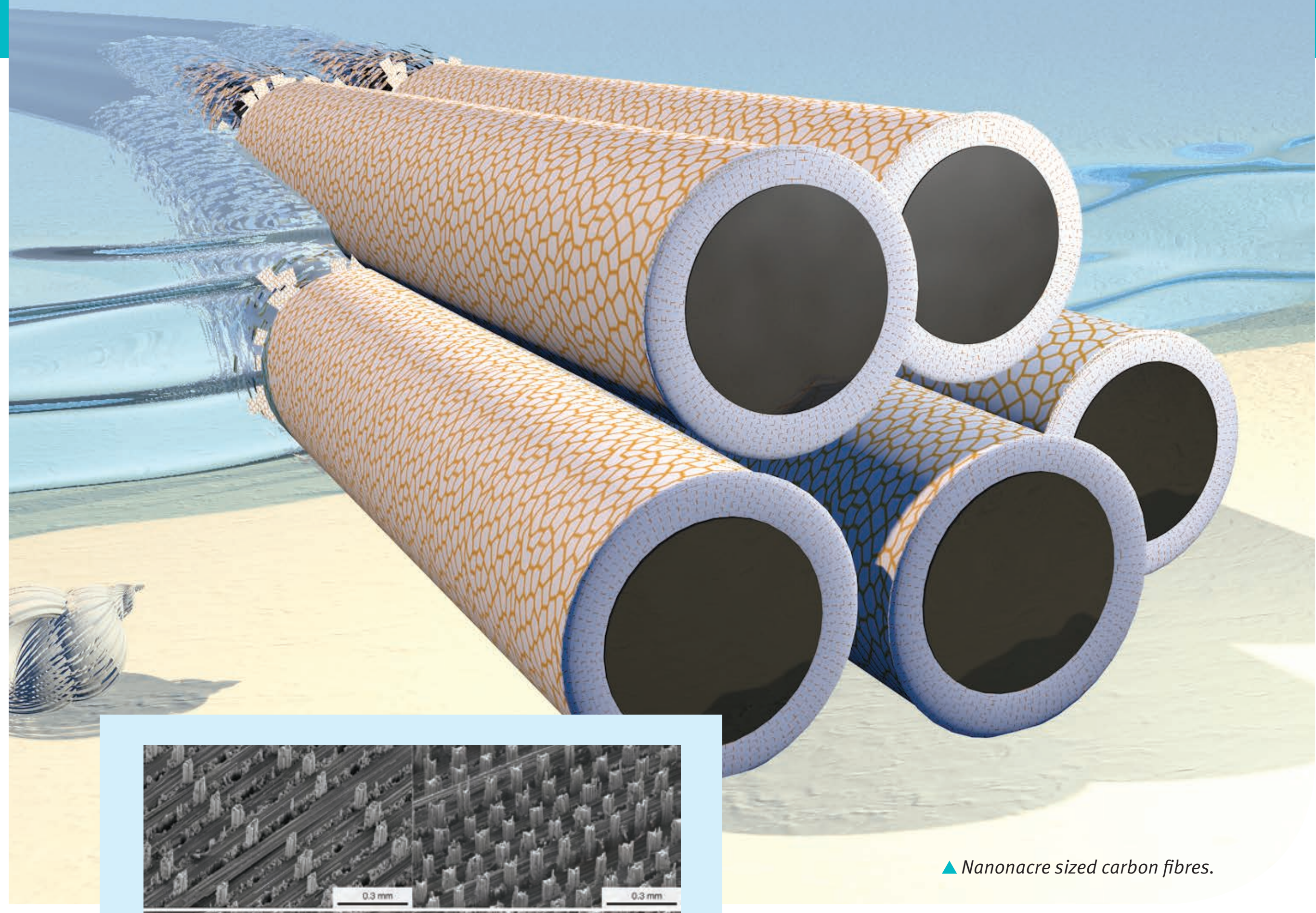
High performance composites generally exhibit brittle failure with little or no prior warning. We have just completed a large research project funded by an EPSRC Programme Grant (held jointly with Bristol University) which has been examining strategies to introduce a more ductile failure process in these composites and has involved staff from the Departments of Chemistry, Chemical Engineering, Mechanical Engineering and Aeronautics.

A variety of mechanisms have been proposed to impart a yielding-like behaviour and to ensure this occurs in a distributed manner under uniform tensile loading. One technique exploits the 'hidden length' in wavy configurations. The wavy skin sandwich panel shown in the Figure below, had a light crushable foam core and exhibited failure strains in excess of 8% and ultimate failure stress of around 1800 MPa.

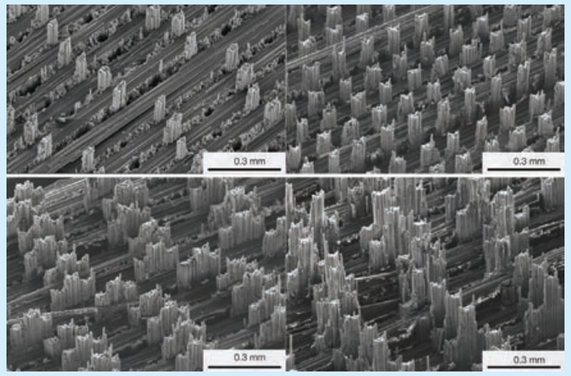
Another approach has looked at the potential of introducing cuts or perforations in selected plies in a laminate. The aim is to initiate delamination growth from these cuts and to ensure that this delamination growth will occur in a stable distributed manner throughout the specimen which is manifested by a yielding characteristic on the tensile stress-strain curve. Using perforations enables the pseudo yield stress to be tailored by adjusting the geometry of the perforation pattern. With this technique the ultimate strain cannot be increased above that of the pristine composite but the yielding-like behaviour could help alleviate premature failure due to stress concentrations. Another advantage of this technique is that the initial stiffness is very close to that of the pristine composite.



▲ *Pseudo ductile composite.*



▲ *Nanonacre sized carbon fibres.*



▲ *Microengineered composite architecture to enhance translaminar toughness.*

05 Engineering fracture surfaces in CFRP: key to damage tolerance

Academic lead • PROF S.T. PINHO

The damage tolerance of composites can be improved via micro-structural design — in fact, by tailoring the local architecture and microstructure, the resulting fracture surfaces can be engineered to enhance the composite performance. To this end, we took inspiration from various natural composites (including wood, bone, nacre and the Gigas shell) and carefully designed CFRP composites with significantly improved damage tolerance.

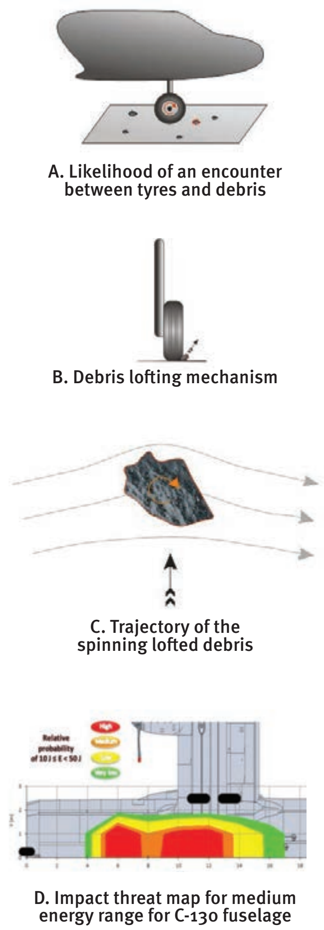
By adopting these approaches, we have obtained an over 60% increase in notched strength and 500% increase in translaminar fracture toughness, as well as improved damage diffusivity. This work is supported by EPSRC (Engineering Fellowships for Growth: Next generation of lightweight composites — how far can we go?).

The maturity of this research is such that our current and future focus will be directed to identifying, investigating and developing suitable industrial applications.

06 Nano-nacre sizing for carbon fibre composites

Academic lead • PROF M. SHAFFER

Conventional fibre-reinforced composites suffer from the formation of critical clusters of correlated fibre breaks, leading to sudden composite failure under tension. To mitigate this problem, an optimized "brick-and-mortar" nanostructured interphase has been developed to absorb energy at fibre breaks and alleviate local stress concentrations whilst maintaining effective load transfer. The coating has been designed to exploit crack bifurcation and platelet interlocking mechanisms known in natural nacre. However, the architecture has been scaled down by an order of magnitude to allow a highly ordered conformal coating to be deposited around conventional structural carbon fibres, whilst retaining the characteristic phase proportions and aspect ratios of the natural system. Drawing on this bioinspiration, a layer-by-layer assembly method has been used to coat multiple fibres simultaneously, providing an efficient and potentially scalable route for production. Single fibre pull-out and fragmentation tests showed improved interfacial characteristics for energy absorption and plasticity. Impregnated fibre tow model composites have demonstrated increases in absolute tensile strength (+15%) and strain-to-failure (+30%), as compared to composites containing conventionally sized fibres. This technology was developed as part of the HiperDuct program to develop high performance composites that manifest significant ductility.



▲ *Phases of the runway debris lofting process.*

07 Prediction of the runway debris impact threat to aerostructures

Academic lead • PROF E.S. GREENHALGH

We have developed and demonstrated a design tool to predict the threat to aircraft from runway debris thrown up by the undercarriage wheels. From runway debris characteristics, aircraft and tyre geometries, and take-off and landing profiles, our model predicts the likelihood of a tyre/debris encounter. We have then numerically modelled the contact mechanisms by which the debris, tyre and runway surface interact to cause lofting and determined the initial direction and speed of the projected debris. All these models were validated against bespoke drop-weight experiments, monitored with high speed video, which reproduced key aspects of the contact conditions between the stones, tyres and ground. This led to a physically-based analytical model which provided an insight into the critical parameters which dictated the severity of the stone lofting processes.

Having established a reliable model for the initial state of the lofted stone at the start of its projected motion, the next stage investigated the subsequent trajectory of the debris to enable prediction of the severity of any resulting impact on the aircraft. Aerodynamic models were developed for the interaction between the spinning lofted stone and the airflow in the wake of the undercarriage wheels and beneath the fuselage. This culminated in 'threat maps' which identify the sites on the lower fuselage that are exposed to the most severe impact conditions. Hence, these maps have been used to identify which sites on the underside of the aircraft need to be armoured to negate the threat from such events. Our models have been adopted by industry to design a nosewheel debris deflector shield for an aircraft now in service. This has dramatically reduced the incidence and severity of the runway debris impacts and the associated maintenance costs and downtime.

08 Aquatic Micro Aerial Vehicles

Academic lead • **DR M. KOVAC**

In nature, several animals have evolved design solutions that enable them to successfully transition between water and air, and to move in both media. Examples include flying fish, flying squid, diving birds and diving insects.

Inspired by the many species of plunge-diving seabirds, we have developed the Aquatic Micro Air Vehicle (AquaMAV), a novel drone with the ability to dive directly into the water from flight, and return to the air. With its 592 mm wingspan and weighing only 200 grams, it flies at 10 metres per second, and has sufficient energy for a 5-km flight range. The miniature aircraft uses folding composite wings which permits it to sustain the hydrodynamic loads encountered in the dive. This wing folding mechanism also allows for fine adjustment of sweep angle and to modify the vehicle's flight dynamics. The system has slight positive buoyancy, so it can float by itself to the surface after a dive, ready to retake flight. A two-speed gearbox can be integrated to allow the robot to use its aerial propeller underwater and perform extended underwater exploration after a dive. To escape the water, the AquaMAV then uses a powerful water jet thruster, which forms the keel of the robot.

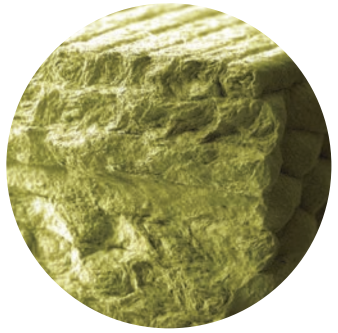
The AquaMAV is dedicated to environmental monitoring and will find use in disaster relief, and oceanography, particularly in areas such as around flooded buildings, or rocky, littoral ecosystems, where obstacles impede the free movement of conventional aquatic vehicles and prevent close observation by purely aerial robots.

▲ *Aquatic micro aerial vehicle entering the water.*

09 Additive manufacturing of ceramic-based composites

Academic lead • **PROF E. SAIZ**

We have been working on the development of additive manufacturing technologies to fabricate ceramic-based composites. In particular, we are concentrating on the use of robotic assisted deposition (robocasting) to fabricate fibre and platelet-reinforced composites. The goal is to build composite parts with a range of geometries that will exhibit complex hierarchical microstructures. To achieve this goal, we are developing ceramic inks with controlled rheology for 3D printing and using external fields to manipulate particle alignment. The microstructures can be designed to direct crack propagation at the microscopic level in three dimensions and develop tough materials with high specific strengths. We have developed a series via in situ mechanical tests in the scanning electron microscope that enables us to identify the salient toughening mechanisms. This work is supported by the CASC Industrial consortium formed by Morgan Advanced Materials, Safran, Asahi Glass, John Crane and Reaction Engines. Extension of the research to new materials combining mechanical and functional properties is being investigated with EPSRC funding (MAPP, Future Manufacturing Hub in Manufacture using Advanced Powder Processes).



▲ *Additive manufactured ceramic composite component.*

▲ *Recycled carbon fibres.*

10 Recycled carbon-fibres and their composites for semi-structural applications

Academic lead • **DR S. PIMENTA**

The world-wide demand for carbon-fibres will reach 100 thousand metric tonnes in 2020, making it imperative to establish recycling routes for carbon-fibre waste. Carbon-fibres can be recovered through pyrolysis, with a few industrial-scale implementations already operating at commercial scales. Recycled carbon-fibres can be recovered using less than 10% of the energy needed to produce new fibres, and obtained at 25-50% of the price of their virgin precursors.

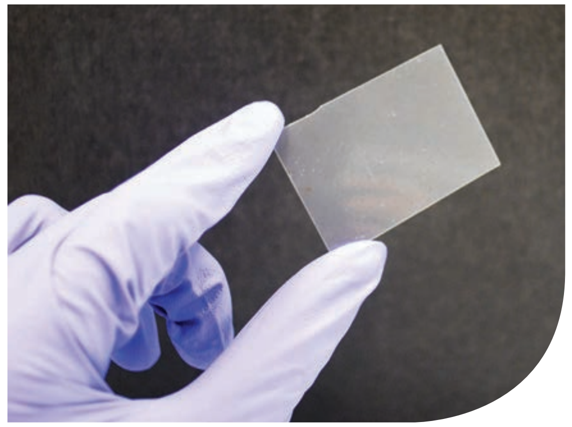
We have benchmarked the morphology, mechanical properties and adhesion of recycled fibres against their virgin precursors for a range of recycling processes. We have shown that batch pyrolysis can recover virgin-like fibres, but continuous pyrolysis implemented at industrial-scale recovers fibres with a wider range of performances, depending on the exact process conditions. We have also correlated fibre-surface damage and loss of fibre-mass with degradation of fibre mechanical properties during recycling.

We have characterised the microstructure and the mechanical properties of recycled composites manufactured through a range of processes, and showed that recycled carbon-fibre composites are a higher-performance alternative to aluminium and glass-composites. We have also shown that residual bundles (i.e. recycled fibres held together by a residual matrix) toughen recycled composites significantly and arrest cracks, and we have developed models to predict this toughening effect. This shows that recycled carbon-fibre composites are suitable for semi-structural applications with damage-tolerance and lightweight requirements, for instance in automotive and aircraft interiors.

11 Nanocellulose composites

Academic lead • **DR K-Y LEE**

Nanometre scale cellulose fibres, or nanocellulose, are an emerging green nano-reinforcement. The major driver for utilising nanocellulose as a reinforcement is the possibility to exploit the stiffness and strength of cellulose crystals. Theoretical calculations and numerical simulations have estimated that the stiffness and strength of cellulose crystals are as high as 180 GPa and 22 GPa, respectively. Raman spectroscopy and X-ray diffraction have also shown experimentally that a single nanocellulose fibre possesses a tensile stiffness of between 100-160 GPa. Tensile strength of a single nanocellulose fibre was estimated to be 1 GPa based on experimental results for elementary plant fibres. Thus, nanocellulose fibres could potentially serve as a replacement for glass fibres given their low toxicity and density (~1.5 g cm^{-3}). We work on microbial-synthesised bacterial cellulose, with a focus on understanding the mechanics of the nanofibre network. This will allow us to engineer the microstructure of the reinforcing nanocellulosic fibres to maximise material performance for various advanced composite applications. We also work on the use of bacterial cellulose as a Pickering emulsifier to produce low density macroporous polymers. Our research is supported by the EPSRC, Climate-KIC, DSTL and the US Army.



▲ *Nanocellulose veil.*

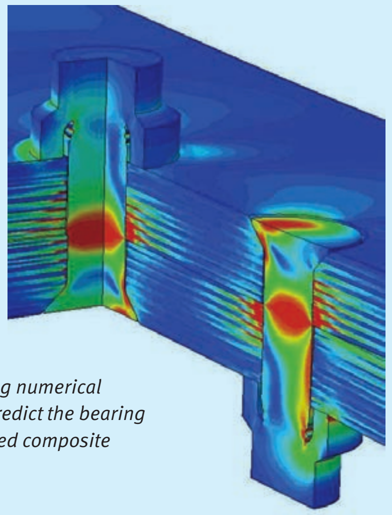
12 Multiscale analysis of composite structures

Academic lead • PROF S.T. PINHO

We have a long tradition of pioneering novel modelling approaches for multiscale simulation of the mechanical response for composites. These include: the first smeared crack model for simulating failure in composites (now available in the commercial releases of Abaqus and LS-Dyna); one of the first cohesive models in explicit FE analyses; failure criteria that were ranked top in the second World-Wide Failure Exercise; a Mesh Superposition Technique that makes multiscale simulation of composite structures more efficient; and more recently the Floating Node Method.

The Floating Node Method allows for complex networks of interacting cracks to be simulated efficiently. We have implemented this method in a commercial FE code and demonstrated the effective simulation of 3D problems involving hundreds of cracks in complex networks involving delamination, splitting, migration of delaminations and fibre failure.

Ongoing and future focus will be directed to using some of the modelling techniques developed as a springboard for the development of a dedicated multiscale design engineering method tailored to specific design scenarios.



▶ *We are using numerical methods to predict the bearing failure of bolted composite components.*

◀ *Researchers are developing the next generation of flying robots, focusing on a range of applications that include search and rescue, in-situ repair, environmental monitoring and exploration of hazardous environments.*

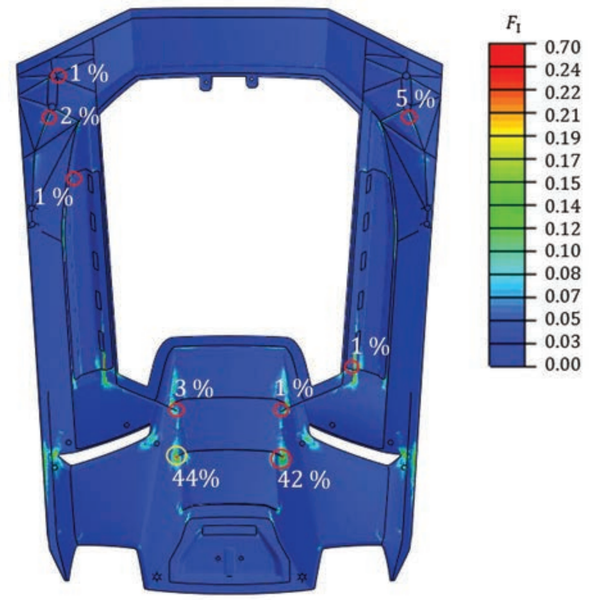
13 Aerial Construction: drones for building, repairing and restoration

Academic lead • DR M. KOVAC

Aerial robots with the capability to autonomously construct structures would be invaluable in many applications: building temporary shelters following natural disasters such as earthquakes and floods, deploying scaffolding and support structures on conventional construction sites, or assembling ramps across gaps and difficult terrain to enable access to terrestrial vehicles.

Aerial Additive Building Manufacturing (Aerial ABM) is a UK EPSRC funded research project that is developing an aerial robotic construction system that enables aerial robots to 3D print building structures autonomously, by deploying tensile elements and/or depositing amorphous composite materials. The work is largely inspired by the way how animals, such as birds and bees, build structures using environmental materials in combination with composites with adhesives and intricate architectural designs.

The research aims to miniaturise robotic systems for Additive Building Manufacturing (ABM) and provide it with aerial capabilities, so that it can be more mobile, and able to manufacture complex building structures while adapting to diverse site scenarios. This miniaturisation will also enable parallel production, where swarms of aerial printers working together could potentially reduce construction time and enable safer construction in hard-to access and dangerous environments.



▲ *Models have been used to design improved material microstructures. The results have been implemented in an FE framework to design automotive components in collaboration with Lamborghini.*

14 High-performance discontinuous composites for high-volume structural applications

Academic lead • DR S. PIMENTA

High-performance Discontinuous Carbon-Fibre Composites (DCFCs) consist of randomly-oriented carbon-fibre bundles embedded in a polymeric matrix. These novel materials can be moulded into complex 3D shapes using fully-automated processes and cycle times as low as 2 min, which makes them suitable for high-volume applications. Moreover, DCFCs have a high fibre content (up to 60% in volume), which allows these materials to retain up to 95% of the stiffness and 60% of the strength of conventional quasi-isotropic continuous-fibre carbon-fibre laminates, while being far more damage tolerant.

The microstructure and failure mechanisms of DCFCs are unlike those of any other engineering material and cannot be predicted with existing material models. In a project funded by the Royal Academy of Engineering, we have developed physically-based models to predict the mechanical properties of DCFCs, and successfully validated them against experiments. These models run in just minutes; they can be used to predict the influence of the microstructure of DCFCs on their local mechanical properties, and to design new microstructures with improved performance.

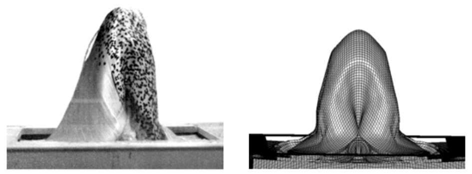
The randomly-placed large bundles in DCFCs lead to a considerable spatial variability of mechanical properties, which may cause structures to fail in unexpected locations. In collaboration with Lamborghini, we have developed a framework to simulate the response of DCFC structures while accounting for this intrinsic variability in mechanical properties. This framework assigns mesh-objective stochastic fields of material properties to Finite Element models of structures, and runs a Monte Carlo statistical analysis to quantify the reliability of the design and identify a range of potential critical regions.

15 Polymeric armour

Academic lead • PROF L. IANNUCCI

Survivability is a significant design issue in civilian applications due to the increased threat of terrorist activity, which has highlighted the vulnerability of vital infrastructure. Research work at Imperial has led to the development of novel constitutive relationships for high performance polymeric materials and analysis procedures, software algorithms for blast and impact. The application of such techniques are not just for defence, but also for passive shields on new composite airframes and engine fragment protection on new engine concepts.

Research projects funded by the EPSRC, European Union, TSB and MoD (Dstl) over the past ten years have contributed to the development of this research area. The overall aim of this research activity has been to develop sophisticated modelling techniques which are capable of simulating the complex phenomena associated with the deformation of polymeric armour materials under high velocity impact loadings. The research has also contributed to the development of sophisticated mesoscale modelling methods for advanced materials and structures, which have been implemented into bespoke and (protected) commercially-available numerical simulation software. The clearer insight into the dynamic response mechanisms of the current protective materials has also provided a strong foundation for the micro-scale design of significantly better systems in the near future. This deeper understanding has also led to the development of fundamentally new armour concepts based on recycled and micro-braided materials.



▲ Prediction and high speed video image from ballistic impact on polymeric armour, demonstrating excellent agreement.

▲ Experimental research is supported by well-appointed laboratories and highly experienced and competent technicians.

▲ Sensorized stiffened composite curved panel.

16 Structural integrity and health monitoring

Academic lead • DR Z. SHARIF KHODAEI

We have developed innovative methodologies and invented technologies for condition based maintenance of aircraft structures. These technologies are applicable to complex composite structures under operational environmental and load conditions. Our patent inventions include diagnostic film (including sensors, wiring, connectors, bonding), wireless passive and wireless active sensing units with energy harvesting for diagnosis and prognosis of impact events. Another recent invention is a multi-functional sensor integrated into a repair patch diagnostic layer (in-situ application) for monitoring curing as well as in-service damage detection. The integrity of these novel technologies has been demonstrated under flight conditions, i.e. temperature, humidity, vibration and mechanical fatigue load. The architecture of the SHM system is designed to record, process and and transmit large amounts of data. In addition to these technologies, our methodologies are developed with high reliability and probability of detection. The multi-level diagnostic algorithm is able to detect, locate and characterize damage in large scale composite structures, under operational load. Our methodologies were tested on a large curved stiffened panel during the CleanSky project SARISTU where damage was successfully detected.

We have an active Group and many successful research projects over the past seven years (CleanSky JTI-SMASH, SCOPE, SARISTU) which have resulted in several patent applications. Currently we are coordinators of a core-partner consortium with CleanSky2 JU called SHERLOC, of seven years duration. We are designing, manufacturing and testing composite parts for affordable fuselages including an SHM system on board where we are testing our technologies following the building block approach. The element level studies include window-frame, floor beam, aft pressure bulkhead joint, fittings and mono-stringer which are then followed by sub-components such as a five-metre curved composite stiffened panel.

▲ Blast experiment on composite component.

17 Blast performance of marine composites

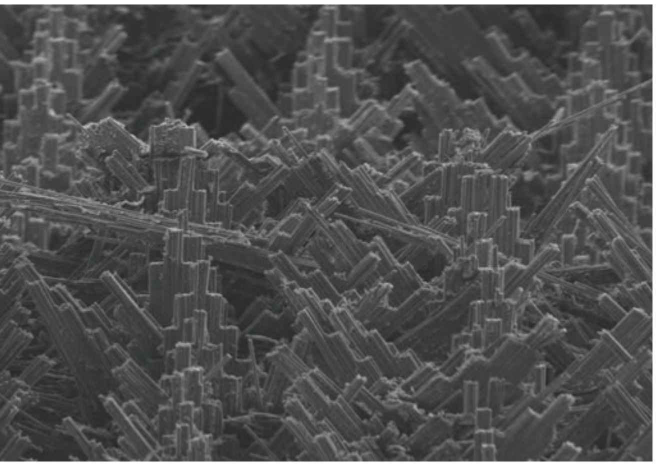
Academic lead • PROF J.P. DEAR

We have developed reliable large-scale experimental techniques to record the panel response during air and underwater blast experiments. This experimental setup has been used to understand the response of a wide variety of marine sandwich structures along with laminated glass. The ability to record full-field data during the blast event using digital image correlation techniques has led to widespread industrial interest and continuous support from the Office of Naval Research.

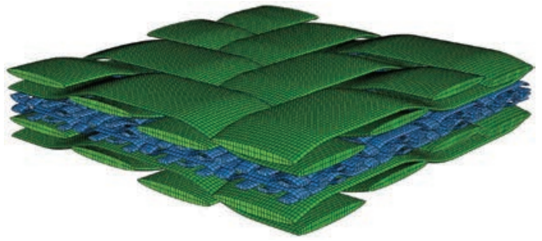
The marine sandwich structures evaluated have demonstrated exceptional blast resilience. A wide variety of materials have been investigated, including various polymer foam cores and face-sheet fibre-reinforcements. The research has revealed the superior performance of SAN polymer foam cores, along with the benefits of implementing a stepwise graded density core with density increasing from the front to the rear of the panel. A graded density core prevents through-thickness crack propagation and results in minor cracking and debonding between core layers. Overall, this results in the retention of greater structural integrity and post-blast strength. Intralaminar hybrid carbon-fibre and glass-fibre face-sheets and the influence of polymer interlayers has been studied. The addition of polymer interlayers reduces front face-sheet cracking which is beneficial for preventing water ingress following a blast event. The combination of glass-fibre and carbon-fibre layers within the face-sheets results in reduced deflection during blast due to interaction and damage development between the dissimilar fibres. The experimental results have led to the development of finite element models which help to inform experimental decisions.

There is huge potential for further use of composite sandwich structures in the naval industry. These large-scale, representative experiments demonstrate the suitability for composite structures under the harsh loads expected in the marine environment.

Research themes



Electron micrograph of a carbon aerogel infused spread tow lamina for structural power composites.



We are using finite element modelling to predict the mechanical response of structural supercapacitors.

Synthesis of New and Multifunctional Materials

THE COMPOSITES CENTRE is very active in the conception and synthesis of new and multifunctional composites. These materials offer properties and functionalities which cannot be achieved with conventional systems, but present considerable processing and characterisation challenges. We introduce nanomaterials into fibre reinforced composites, and by having addressed the manufacturing issues, are now fully exploiting the properties of the nanophase in the resulting composites. We are world leading in the field of multifunctional structural power composites: structural composites which have multiple functionalities, such as electrical energy storage. Despite being a relatively new field, multifunctional composites are quickly emerging as vital for the future transportation and mobile electronic sectors. Finally, we are addressing fundamental aspects of composites, such as their inherent brittleness, through the development of ductile composites.

(Pseudo-) Ductile and damage tolerant discontinuous composites

DR S. PIMENTA, PROF P. ROBINSON

We have developed novel models to design discontinuous composites with a progressive failure and non-linear response. This has led to the development of (pseudo-) ductile discontinuous composites based on cut-prepregs with aligned short fibres, fibre hybrids and bio-inspired hierarchical microstructures with an initial stiffness akin to that of continuous composites but a more gradual and energy dissipative failure process.

Structural power materials

PROF E.S. GREENHALGH, PROF M. SHAFFER, PROF A. KUCERNAK, DR K-Y LEE

We are world-leading in the development of structural supercapacitors – structural composites which have the ability to store/deliver electrical energy. These materials offer considerable performance advantages whilst presenting compelling opportunities for innovative design. We have a large portfolio of research addressing the fundamentals of these materials, manufacturing and design issues, mechanical properties and applications.

Composites with stiffness control and shape memory capabilities

PROF P. ROBINSON, PROF A. BISMARCK

We have developed composites which exhibit controllable stiffness and shape memory. One type consists of a carbon fibre thermoset laminates containing thermoplastic interleaf layers and another consists of thermoplastic coated carbon fibres in a thermoset matrix. The loss in shear stiffness of the thermoplastic at elevated temperature results in the temporary loss in flexural stiffness of the composite. These composites may find applications in deployable and adaptive structures.

Micro engineering the composite architecture

PROF S.T. PINHO, DR S. PIMENTA

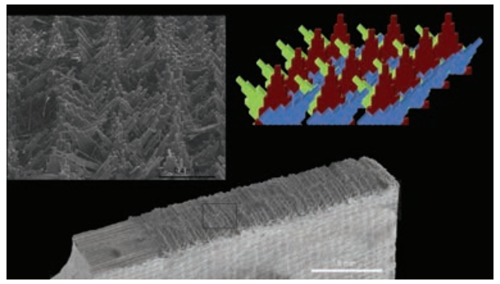
The damage tolerance of composites can be improved via micro-structural design. In fact, their fracture surfaces can be engineered by modifying their micro-structure accordingly. Inspired by nature, we have designed composites to create hierarchical pull-out features during fracture, tiled micro-structures and cross-lamellar microstructures. Using these approaches we have obtained increases of over 500% in translaminar fracture toughness, as well as improved damage diffusion.

Hierarchical composites

PROF M. SHAFFER, PROF E.S. GREENHALGH, PROF A. BISMARCK

We have developed hierarchical composites; reinforcement at both the micro- (carbon fibres) and the nano- (CNTs, carbon aerogel or graphene) scales. We have two approaches to achieve high loading fractions of the nanophase; via matrix reinforcement and via growing CNTs on the fibres, achieving extremely high-volume fractions of the nanophase. This has led to huge improvements in performance over conventional systems as well as added functionalities.

Development of new multifunctional structural power materials.



We have been tailoring the microstructure of composites to enhance their resistance to crack growth.

Nanocarbon reinforced lightweight metal composites

DR Q. LI, PROF M. SHAFFER

Nanocarbon reinforced lightweight metal composites such as Mg, Al and their alloys are produced via a melting process. Controlled dispersion of the nanocarbon through physical and chemical approaches to achieve a homogeneous dispersion and tailored microstructure, has been investigated. The composites obtained have improved mechanical and physical properties over those of the parent metal.

Nanocarbon reinforced polymeric composites

DR Q. LI, PROF M. SHAFFER, PROF E.S. GREENHALGH

Nanocarbon reinforced polymer composites have been produced by various methods, including solution casting, hot pressing and 3D printing. Both nanocarbon and carbon nanotube veils have been investigated as reinforcements. The objectives are to develop suitable manufacturing methods to process strong and lightweight polymer composites, as well as enhance the thermal and electrical properties.

Composite Design, Life Cycle Analysis and Recycling

Composites encompass a huge diversity of different constituents, architectures and applications, and hence designing with these materials presents considerable challenges, particularly for new adopters. Although the raw materials are expensive, unlike metallics, composites are not as susceptible to fatigue and corrosion, and hence ownership costs for composite components can be superior. The Composites Centre has extensive experience in composite design, ranging from established (such as aerospace) to emerging (such as infrastructure) applications. We have expertise in life-cycle analysis of composites, including recycling, and particularly in modelling of the performance of components manufactured from recycled composites.

Analysis of recycled fibres and composites

DR S. PIMENTA, PROF S.T. PINHO

We have analysed state-of-the-art recycled fibres and composites in conjunction with industry. A cornerstone contribution was to show that residual fibre bundles (until then perceived as defects) actually enhance the fracture toughness and damage tolerance of recycled composites. Our work on characterisation and modelling of recycled composites has been recognised internationally.

Design for the threat of runway debris to aircraft structures

PROF E.S. GREENHALGH, PROF L. IANNUCCI

Runway stones thrown up by aircraft undercarriage can cause considerable damage. Models have been developed which capture the wheel encounter with the stone, the lofting physics, stone trajectory and hence the severity of the impact on the aircraft structure as 'impact threat maps', thus informing design decisions. This model has successfully been used in the development of an aircraft now in service.

Binderless natural fibre preforms and their composites

DR K-Y LEE, PROF A. BISMARCK

We have developed an elegant, intrinsically scalable and cost-effective technology for binding fibres together to create an in-plane non-woven fibre mat, utilising bacterial cellulose. Truly green non-woven fibre preform reinforced hierarchical composites have been prepared by infusing the fibre preforms with acrylated epoxidised soybean oil using vacuum assisted resin infusion, followed by thermal curing. Both the tensile and flexural properties of these hierarchical composites presented significant improvements over the parent materials.

(Nano)cellulose for advanced composites applications

DR K-Y LEE

Nanocellulose fibres could be used as a structural reinforcement, and could potentially serve as a replacement for glass fibres given their low toxicity and density. We are tailoring the reinforcement architecture of various types of nanocellulose within the polymer matrix to produce composites for various applications such as transparent armour.

Aerial Aquatic Drones

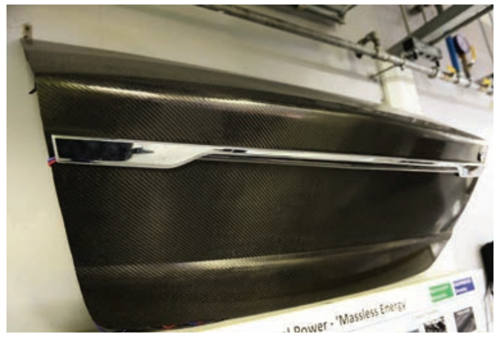
DR M. KOVAC

We have abstracted the underlying design principles from nature to build and demonstrate robotic vehicles which can move in both air and water: the Aquatic Micro Air Vehicle. Designing multimodal MAVs that can fly effectively, dive into the water and regains flight would enable applications of distributed water quality monitoring, search and rescue operations and underwater exploration.

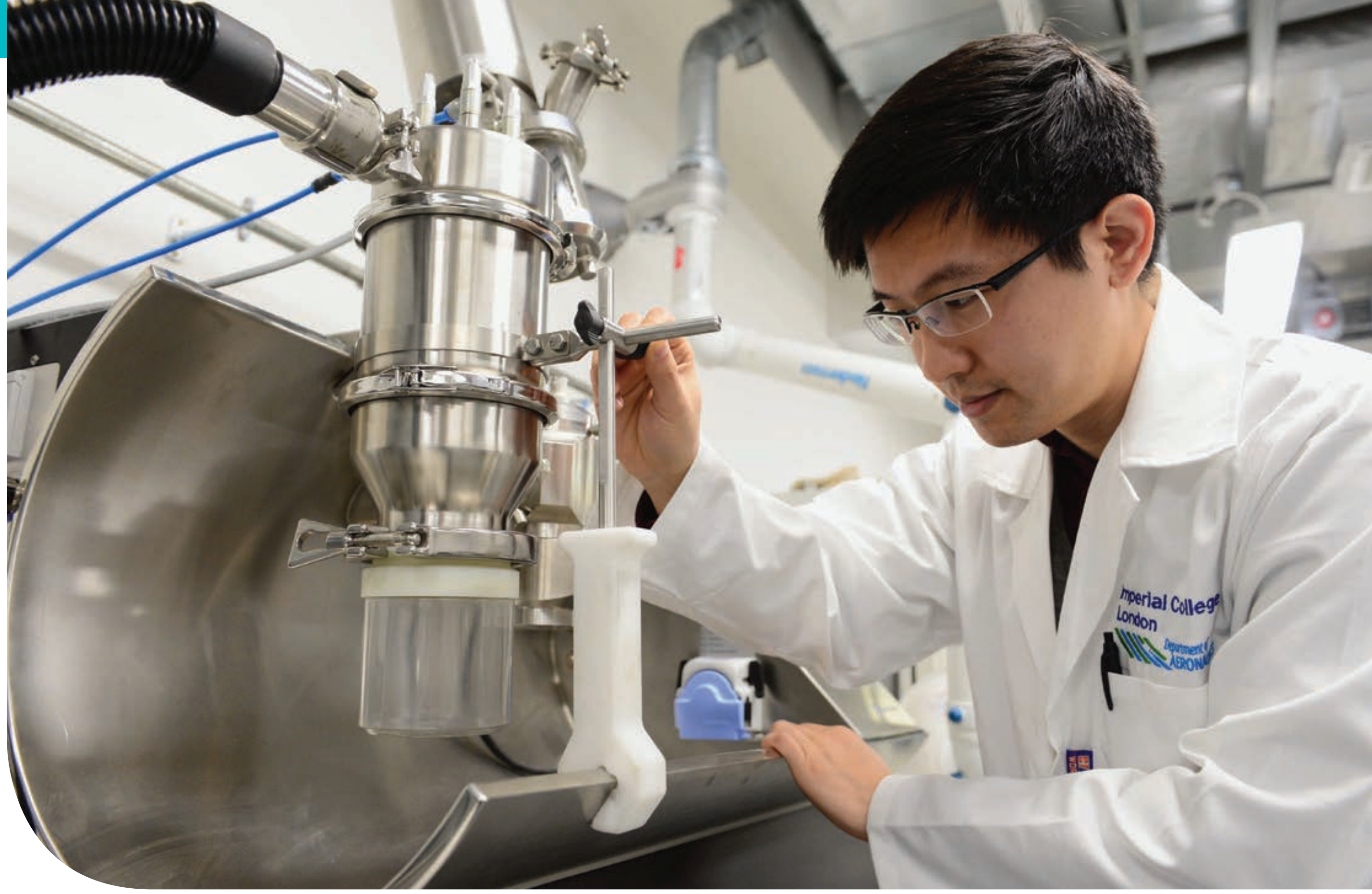
Design methodology with multifunctional materials

PROF E.S. GREENHALGH, PROF M. SHAFFER, PROF A. KUCERNAK, DR K-Y LEE

Multifunctional materials offer considerable savings in system-level mass and volume, hence contributing to reductions in energy consumption. However, given this field is relatively immature, the design methodologies to facilitate adoption by industry are fairly limited. We are developing analysis tools to predict performance requirements and design strategies for using multifunctional materials.



▲ *Multifunctional bootlid for a Volvo S80 made using structural supercapacitors to supplement the electrical energy storage.*



▲ *We are developing new natural composite constituents.*

Design for next generation of lightweight structures

DR A. PANESAR

This research realises the next-generation lightweight parts and fully utilizes the inherent design freedom of additive manufacturing by employing a topology optimised design procedure that includes the anisotropic considerations for continuous fibre printing of variable stiffness composites. Polymer-based end-use parts from additive manufacturing can enhance stiffness and allow for tailored structural performance. Benefits for a wide range of industries is anticipated, especially for aerospace and automotive sectors.

Composite and multidisciplinary design optimisation

DR R. HEWSON, DR M. SANTER

We are developing techniques for optimisation of stacking sequences of composite laminates to tailor the elastic response. This has been applied to reduced order beam models for aeroelastic tailoring of forward swept wing aircraft and fibre wound cylinders. This work was undertaken with aerodynamic research colleagues at ONERA in France.

Foam-templated macroporous polymers

DR K-Y LEE, DR V. TAGARIELLI

We have developed a simple, intrinsically scalable, rapid and waste-free manufacturing process for epoxy foam cores with densities of 0.18 g cm^{-3} without the need for a blowing agent. This process is based on the principle of liquid-foam templating, whereby an uncured epoxy resin is mechanically frothed and then can then be poured, shaped or moulded, followed by curing. Unlike the production of conventional foam core materials, no expansion or shrinkage occurs during curing.

Design of polymeric armour

PROF L. IANNUCCI

A continued need exists for high performing, lightweight and cost-effective protection for personnel and vehicles to improve survivability and reduce injury. Such protection must cover threats which generate extreme loadings, e.g. blast and ballistic impacts. Most polymeric armours use high performance fibres, which do not exhibit the brittle nature of high stiffness carbon and glass fibres. To understand the behaviour of such systems, material modelling has been developed capable of predicting the ballistic performance of polymeric armours.

Composite Manufacture and Repair

Manufacture has been a critical bottleneck in the uptake of composites by industry, and the rapidly expanding and changing portfolio of composite constituents and architectures means a diverse range of processing routes need to be developed and understood. The Composites Centre has a knowledgeable and experienced team of staff to support this area as well as diverse range of facilities for research and development of composite manufacture. In parallel, we have expertise in predictive modelling processes associated with composite manufacture and repair.

Interleaved composites for easy repair of impact damage

PROF P. ROBINSON, PROF A. BISMARCK

An 'easy-repair' laminate concept has been developed to address the repair problem posed by interlaminar damage due to impact. A conventional carbon epoxy laminate is interleaved with a material which can thermally bond to itself, such as Polylactic Acid (PLA). On impact the interleaved composite would fail within the interleaf layer due to impact. The laminate is then heated to initiate bonding, perhaps accompanied by external pressure, and so restoring its initial pristine state.

Aerial additive building manufacturing

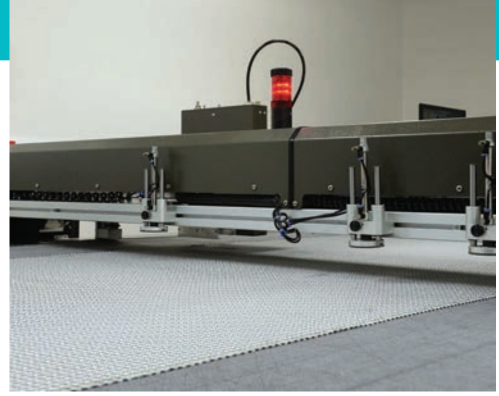
DR M. KOVAC

Utilising aerial robots to construct structures would be invaluable, particularly in applications such as disaster relief. However, construction in unstructured environments would require aerial robots that adapt to terrains and layouts unique to individual physical sites. Our goal is to develop novel autonomous manufacturing methods by investigating techniques for building physical structures with aerial robots.

Manufacture of multifunctional materials

PROF E.S. GREENHALGH, PROF M. SHAFFER, PROF A. KUCERNAK, DR K-Y LEE

Having demonstrated multifunctional composites, one of the critical challenges is now to scale-up the manufacture of these materials. This includes dealing with fabrication and assembly of multiple devices, encapsulation and hybridisation with conventional materials, making curved components and electrical integration with the surrounding structures. We are investigating how to make composite components using these materials, and addressing the critical research challenges which hinder the uptake of this emerging class of materials by industry.



Ply cutter for dry fabrics and prepregs.

CFD simulation of RTM processes

DR J. PEIRO

The research is aimed at developing fast and accurate Computational Fluid Dynamics (CFD) methods for modelling and simulation of processes for manufacturing textile composite components with bi-directional and woven fabric geometries via resin infusion methods. The overarching aim is to encourage and facilitate their industrial use in the early-design stages of composite structures. Current interest is to extend these techniques to the modelling of manufacturing using thermoplastics.

Multifunctional composites via additive manufacturing

DR A. PANESAR, DR K-Y LEE

The recent developments in additive manufacturing have enabled the fabrication of composite components with tailored geometries which through traditional processes would have been either very challenging or impossible. However, these components often suffer from poor performance. This research is understanding the process- and material- related aspects to realise composites not only with high fibre content and superior mechanical properties but also with embedded functionalities.

Repair of composite components

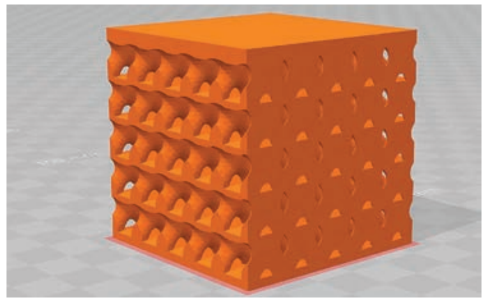
DR Z. SHARIF KHODAEI, PROF M.H. ALIABADI

With new aircraft featuring composites in their primary structures, their repair whilst in service needs to be addressed by the maintenance and repair organizations (MROs). The structural integrity group in the Aeronautics department have been involved in developing smart bonded repair concepts to monitor the bonding quality of the composite patch repair as well as its integrity during operation. Various sensor technologies have been developed and tested to monitor the integrity of the bondline.

We have the capability to vacuum form multifunctional composite components.

Composite Analysis, Modelling and Prediction

Over the last thirty years, the Composites Centre has pioneered analysis and modelling of composites, and now are world-leading in this field. Models developed within the Composites Centre underpin many of the commercial predictive finite elements codes, such as ABAQUS. The research into analysis and prediction in the Composites Centre is diverse including composite failure prediction, damage growth modelling, impact behaviour and material design.



We are using topology optimisation as a means to design the microstructures of novel multifunctional materials.

Development of failure models and criteria for composites

PROF S.T .PINHO, PROF P. ROBINSON, PROF L. IANNUCCI, DR S. PIMENTA

We have developed physically-based failure models for various composite materials, including unidirectional (UD) and woven plies. Our models were ranked top in an international benchmark exercise and have been integrated in the commercial releases of the finite element codes. We have also developed analytical models to predict the mechanical response of unidirectional composites under longitudinal tension, predicting damage accumulation with progressive loading, stochastic size effects on strength, and the influence of fatigue on the tensile failure process and load-carrying ability.

Topology optimisation for multifunctional material design

DR A. PANESAR, PROF E.S. GREENHALGH

This research sets out to address a question "can we design the optimal microstructure to fulfil both structural and functional requirements?" We are currently developing a design-optimisation framework capitalising on topology optimisation methods to realise multifunctional materials. Preliminary investigations into the design of composite materials that offer both high stiffness and high ionic transport to maximise structural power functions (i.e. load bearing energy storage systems) have been promising.

Stochastic modelling of heterogeneous materials

DR V. TAGARIELLI, DR A. SCHIFFER

How do we predict the mechanical response of large composite structures using as input the measured response of small coupons? What is the relation between tensile strength and fracture toughness in brittle and quasi-brittle materials? To answer these questions we have conducted experiments and developed models focusing on stochastic aspects of the mechanical response of materials, and in particular the through-thickness loading of fibre composites.

Modelling the electro-mechanical response of CNT-polymer composites

DR V. TAGARIELLI, PROF S.T. PINHO

Recent technological advances have allowed economical manufacturing of relatively cheap polymer composites reinforced by carbon nanotubes (CNTs). A small volume fraction of reinforcing CNTs (below 1%) imbues electrical conductivity and self-sensing to the polymeric composite, making it suitable for a number of applications. We have developed theoretical and numerical physically-based models to predict the strain sensing response of these materials. We have then developed machine learning techniques to perform such predictions with enormous savings in computation time.

Blast response of composite structures: measurements and modelling

DR V. TAGARIELLI

We have developed new experimental techniques to observe, at the laboratory scale and without the use of explosives, the response of composite structures to blast in air and water. We have used these techniques to validate theoretical and numerical predictive models of these events. These models have allowed optimization of monolithic and sandwich composite structures subject to the threat of explosion, providing valuable tools to design engineers.

Multi-scale models for damage and deformation process prediction in highly filled polymer matrices

PROF M. CHARALAMBIDES

Modelling the deformation and failure processes in highly filled composites (approximately 95% volume fraction) is extremely complex as the very wide particle size distribution necessitates the development of multiscale models in the form of hierarchical simulations. The particle/matrix interface is characterised with a bi-linear cohesive law whereas the soft matrix is modelled through visco-hyperelastic or visco-plastic models. Once calibrated, the material laws are implemented in finite element models which allow the macroscopic response of the composite to be simulated.

Determination of Mixed-Mode Cohesive Zone failure parameters using Digital Volume Correlation and the Inverse Finite Element Method

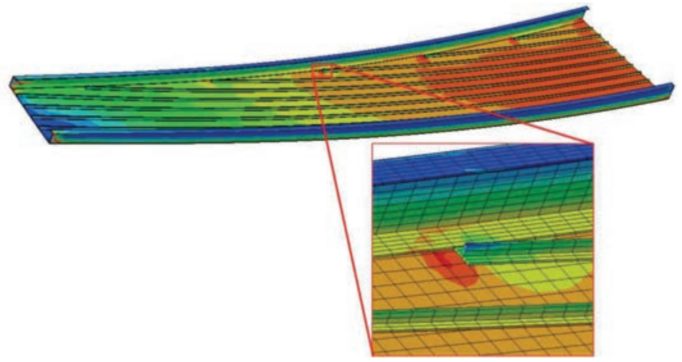
PROF M. CHARALAMBIDES

Experimental determination of the mixed-mode cohesive zone model parameters is very challenging. We are investigating this using digital volume correlation (DVC) data and the inverse finite element method. DVC data are derived from compression experiments of a PDMS (Polydimethylsiloxane) cylinder with a spherical inclusion. Full factorial experiments are being performed for the four cohesive parameters in order to determine the target cohesive fracture energies and damage initiation stresses through an inverse optimisation technique.

Mechanical and electrical modelling of multifunctional composites

PROF E.S. GREENHALGH, PROF M. SHAFFER, PROF A. KUCERNAK, DR K-Y LEE

We are developing models to predict the electrical and mechanical performance of structural power composites. The mechanical models are investigating the compaction of the laminates during fabrication and subsequently the in-plane shear loading response. The electrical models are characterising the charge/discharge behaviour of the devices. These models utilise the constituent properties, and hence facilitate parametric studies for optimisation. This activity will couple the mechanical and electrical models to predict interactions, and ultimately support qualification of structural power composites.



▲ *We have the capability to embed local, detailed, models into larger, component scale models to predict the elastic and failure response.*

High Strain Composites

DR M. SANTER

The use of thin composite flexures as compliant hinges for deployable space structures is extremely attractive due to their capability to self-deploy through the release of stored strain energy and to self-lock upon deployment through controlled buckling. Ongoing research in this field includes: numerical modelling of folding and deployment; characterizing the failure of extremely thin composite structures; high-precision manufacture of high strain composite flexures. The effects of long-term stowage are also the subject of investigation.

Aeroelastic tailoring

PROF R. PALACIOS, DR R. HEWSON, DR M. SANTER, DR A. PARANJAPE

The properties of composites can be harnessed to shape the large-scale deformation of aerostructures under aerodynamic forces. We are building high-fidelity computational models for optimization of composite layup in coupled fluid-structure interaction environments, and seek combined passive/active solutions in which aeroelastic tailoring is complemented by feedback control systems.

The Floating Node Method

PROF S.T. PINHO

The floating node method allows for complex networks of interacting cracks to be simulated efficiently. We have implemented this method in a commercial finite element (FE) code and demonstrated the effective simulation of 3D problems involving hundreds of cracks in complex networks involving delamination, splitting, migration of delaminations and fibre failure.

Multiscale analysis of composites

PROF S.T. PINHO

We work on various multi-scale modelling approaches for the analysis of failure in composites. Recently, we developed a Mesh Superposition Technique which can link different types of elements without creating artificial stress concentrations and without reflecting stress waves in dynamic problems.

Molecular Dynamics Finite Element Method

PROF S.T. PINHO

We have developed a molecular dynamics finite element method which allows for efficient simulation of complex atomistic structures atom by atom. This method represents the force fields from molecular dynamics exactly, but runs (as superposed non-linear user-elements) inside a finite element architecture. This makes it ideal for multiscale simulations with multiscale transitions to continuum descriptions.

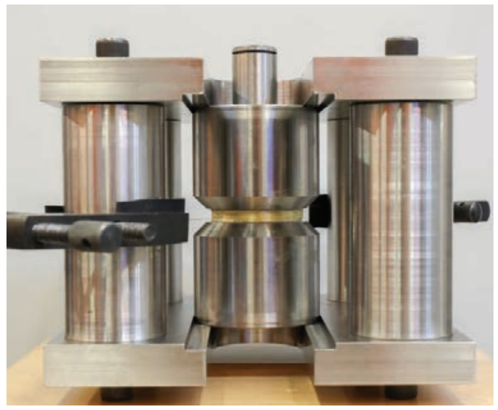
Randomly-oriented tow-based discontinuous composites

DR S. PIMENTA

Randomly-oriented tow-based discontinuous composites are a new class of composites which can be processed in less than five minutes, and are as stiff and even tougher than conventional laminates. Dr Pimenta's Group has experimentally demonstrated the equivalence between randomly-oriented discontinuous composites and layer-by-layer laminates, and has hence developed models for the response of these materials. These have been used to design improved material microstructures, and have been implemented in an finite element (FE) framework to design automotive components.

▲ *We are using in-situ testing within a scanning electron microscope to characterise damage and failure of composites.*

▼ *We are developing new methods to characterise composites under high rates of loading.*



Experimental Mechanics

Research and development associated with the mechanical characterisation of composite materials and components is undertaken in the Composites Centre. Such studies provide an insight into the damage and failure mechanisms in these materials, and provide validation for predictive models. We have considerable experience in undertaking standard test methods for characterisation of new and current composite materials. But we have particular expertise in development of bespoke test methods to characterise composite materials, elements and components.

Measurements of the high strain rate response of advanced materials

DR V. TAGARIELLI, PROF P. CURTIS

Materials such as high-performance fibres, composites and ceramics are often used in applications that involve intense dynamic loading. The measurement of their performance at high strain rates using established methods can be unreliable. We have developed a new test technique which provides valid dynamic measurements in both the elastic and inelastic regimes. The new technique allows tensile testing of arbitrary lengths of high performance fibres, yarns, and monolithic materials, at strain rates up to 10000/s.

Delamination

PROF E.S. GREENHALGH, PROF P. ROBINSON

We have pioneered understanding, characterisation and development of modelling methodologies for delamination growth in composites. We have led development of test methods to characterise delamination under quasi-static, high rates and under cyclic loading. More recently, we have worked on delamination growth at non-zero ply interfaces, using fractographic insights to motivate the development of new test methods to characterise delamination migration. These profound insights into delamination growth have underpinned predictive model development and formulation of methodologies for damage tolerant design.

Environmental effects on composites

PROF E.S. GREENHALGH, PROF S.T. PINHO, DR S. PIMENTA, PROF P. ROBINSON

Under ATI (Aerospace Technology Institute) and industry funding we are characterising the influence of moisture, temperature and rate on the mechanical performance of highly toughened aerospace composites, with the results being complemented by fractographic studies. By investigating the equivalence of the fracture processes under different environmental conditions, we are developing new TTSP (time-temperature-humidity superposition principle) models which link rate, temperature and moisture effects in these materials. The aspiration is to shorten the certification process for aerostructures.

Translaminar fracture toughness

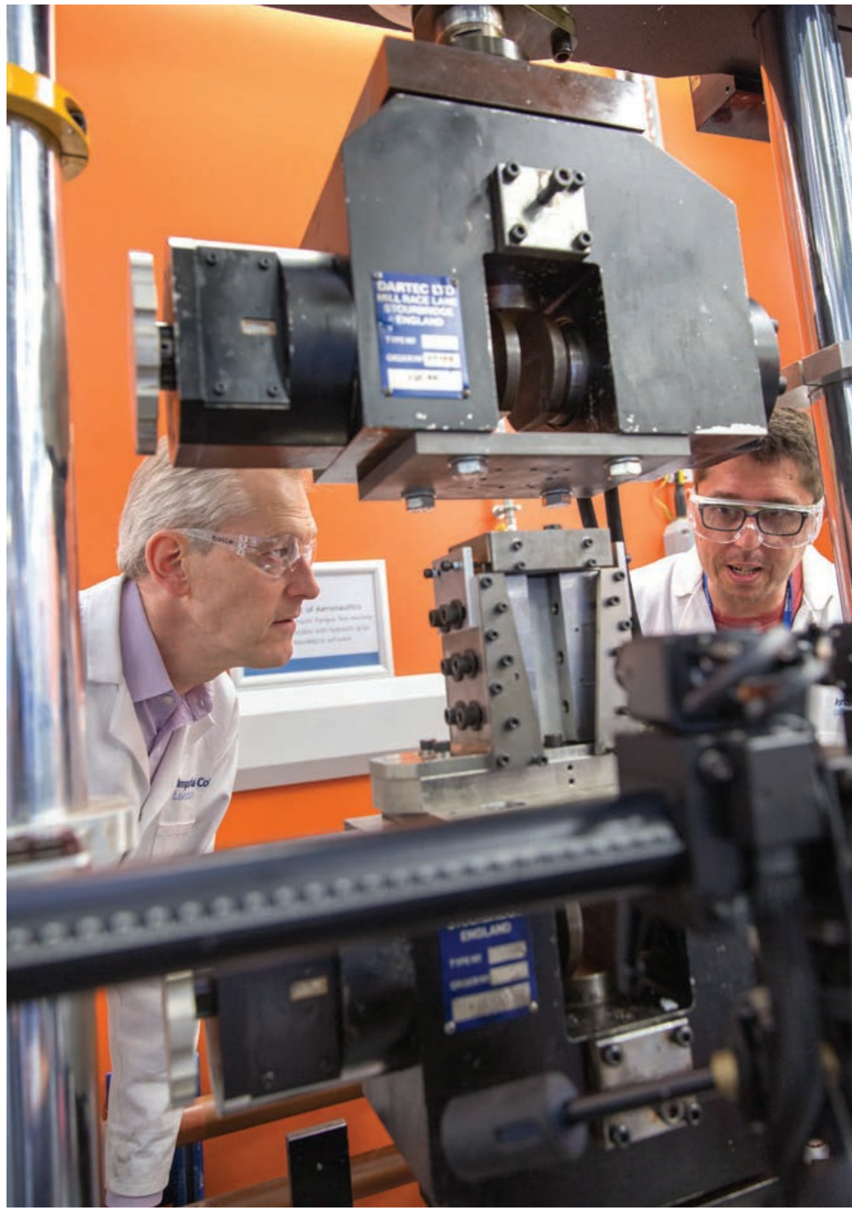
PROF S.T. PINHO, PROF P. ROBINSON, PROF L. IANNUCCI, DR S. PIMENTA

The translaminar fracture toughness of CFRP (Carbon fibre reinforced polymer) plies and laminates defines how translaminar cracks may propagate. We have developed a now widely adopted test method to measure this property. Over the last decade, we have used this test method to characterise different material systems, fibre architectures, recycled composites, size effects, and have also adapted the specimen design and test method to suit a variety of emerging materials.

Impact on composites

PROF L. IANNUCCI, PROF E.S. GREENHALGH, PROF P. ROBINSON

Impact, and its subsequent effects on the mechanical performance of composite structures, has been an important focus of the research in the Composites Centre. We have characterised impact response and thresholds, the influence of impactor and component parameters, and issues such impact whilst under load. In parallel we have developed predictive models for the impact response, damage threshold, damage development and residual performance. We have investigated a spectrum of impact conditions, from low velocity impacts, medium velocity (e.g. runway debris) to high velocity (e.g. ballistic impact).



▲ *Compression after impact testing of a composite laminate.*

Blast performance of composite sandwich panels

PROF J.P. DEAR, DR P. HOOPER, DR H. ARORA

This research group has continued to develop and test composite sandwich panels against full-scale explosive charges, pushing the materials to their limits yet demonstrating their exceptional blast resilience. The high strength-to-weight ratios and energy absorption capabilities of composite sandwich panels make them an attractive choice for many demanding applications, including within the defence sector. The group has developed reliable large-scale experimental techniques to record panel response during air and underwater blast events.

▲ *We use X-radiography to non-destructively characterise damage in composite structures.*

Composite Inspection and Characterisation

The increasingly complicated composite formulations and in-service conditions, as well as the advent of multifunctional composites, means inspection and characterisation of composites is challenging and requires well developed expert knowledge. The Composites Centre is world-leading in fractography of composites, which is used to underpin the research into composite damage and failure processes, and bridge between experimental observations and predictive models. There is also considerable activity on inspection methods for composites, including development and advancement of structural health monitoring methods for composite components.

Fractography of composites

PROF E.S. GREENHALGH

Professor Greenhalgh is world-leading in fractography of polymer composites. This discipline has been employed for studying micro-mechanisms in composite materials, investigation of failures in structural components, through to post-mortem investigations, both in-service and from industry. This includes litigation cases and undertaking accident investigations. Finally, Prof E.S. Greenhalgh teaches a module on fractography as part of the Composites MSc and has delivered short courses on polymer composite fractography to industry.

Structural health monitoring of composite structures

DR Z. SHARIF KHODAEI, PROF M.H. ALIABADI

Structural Health Monitoring (SHM) is an emerging technology covering the development and implementation of technologies and methodologies for monitoring, inspection and damage assessment based on integrated sensors. The acquired data in combination with advanced signal processing techniques can provide maintenance actions upon demand. We have developed various SHM methodologies and technologies for structural diagnosis of metallic and composite structures. We have been and are currently part of numerous EU funded SHM projects (e.g. SARISTU and SHERLOC).

Development of image-based numerical models for predicting the microstructure-property relationship in particulate composites

PROF M. CHARALAMBIDES

Numerical methods that can provide predictions of the mechanical response of particulate polymeric matrix composites as a function of volume fraction and particle mean diameter are needed as a design tool for composites engineers. A generic methodology has been derived, and the model predictions for the modulus and fracture strength are validated through independent experiments on the composite. This paves the way for a relatively simple methodology for determining structure-property relationships in composites design.

We are world leaders in fractographic analysis of composites and regularly support industrial and in-service failure investigations

Research and academic staff

Imperial people share ideas, expertise and technology to find answers to the big scientific questions, engineering hurdles and tackle global challenges.

With the composites research staff in the College spread across a broad range of disciplines, the Centre has been able to develop an unusually diverse research portfolio. There are over thirty academics across the College affiliated to the Centre, and their research covers an enormous breadth of topics, ranging from the development of new composite constituents and architectures, manufacturing routes and characterisation techniques to predictive modelling and design for final applications.

Professor M. H. Ferri Aliabadi

Chair in Aerostructures

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Prof Aliabadi's current interests include fracture and damage mechanics, reliability and robust based optimisation, Multiscale Material Modelling and Structural Health Monitoring. He has led several large EU funded projects (SEAT,SMASH,SCOPE) with the latest project in SHM being a 10M€ cleansky II, core-partnership SHERLOC working toward developing a smart (highly sensorised) composite airframe.

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Dr Bamber Blackman

Reader in the Mechanics of Materials

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Dr Blackman's research interests include the fracture mechanics of structural adhesive joints and polymeric fibre-reinforced composite materials, including effects of mode-mixity, test rate, service environment and structure-property relationships. He has published over 50 refereed research papers and book contributions and has presented his research widely at international conferences. He has served as Guest Editor to the International journal, Engineering Fracture Mechanics on three occasions.

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Professor Maria Charalambides

Professor of Mechanics of Materials

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Prof Charalambides is the Head of the Soft Solids Research group. Her published research includes material modelling and mechanical characterisation of soft polymeric solids, micromechanics models of particulate filled polymeric composites as well as cellular structures, experimental and numerical modelling of industrial food processes, development of inverse indentation methods material characterisation of polymers, and fracture and deformation in coatings. Maria has published over 100 papers and has received funding from industry and RCUK.

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Professor Paul T. Curtis

Senior Research Investigator

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Prof Curtis worked for 39 years as a Senior Fellow in Dstl (and its forerunner establishments RAE, DERA) and is a recognised world expert in the field of polymer composite materials, especially for aircraft structures. He has worked closely with industry in the development and exploitation of these materials. Having retired from MoD, he now has a part time role in the College. He is currently working on developing polymer composite protection materials.

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Professor Alexander Bismarck

Professor of Advanced Materials

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Prof Bismarck's research group, the Polymer & Composite Engineering Group, is a multidisciplinary team with research interests in the manufacture and characterisation of fibre reinforced high performance nanocomposites, porous materials and hydrogels. They focus on the development of renewable materials, biomaterials for applications in tissue engineering, composite supercapacitors and emulsion templating for the synthesis of porous polymers. Furthermore, the group is interested in the social dimensions of materials research.

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Professor John P. Dear

Professor of Mechanical Engineering

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Prof Dear is Head of the Composites, Adhesives and Soft Solids Group and Executive Co-Director for the two AVIC Centres. His research expertise is structural integrity of materials including manufacturing and micro-structural effects. His work includes: impact performance of aerospace and automotive components, blast performance of laminated glass facades and composite structures, creep life of materials and high-strain rate properties of polymers, composites and a wide range of other materials for defence and medical applications.

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Dr Frank Gommer

Composite Research Specialist

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Dr Gommer manages and develops the Composites Suite, and has considerable experience and knowledge in manufacture, finishing and characterisation of composite materials and components. He has a deep interest in the research, design and application of fibre reinforced composite materials to industrial problems. This includes the production of composite parts as well as the prediction of their final properties by analytical and numerical methods.

Dr Barbara Gordon

Senior Research Investigator

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Prior to joining Imperial, Dr Gordon worked in industry for 38 years, principally in the field of aircraft composite structures. This has involved work across the whole product lifecycle. She currently works with a number of members of the group on a variety of topics from new material and product development, through qualification and certification issues to in service damage and repair.

Professor Emile S. Greenhalgh

Professor of Composite Materials, Head of the Composites Centre, Director of the Composites MSc

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A widely respected academic with over 31 years experience in initiating, developing, conducting and managing composites research whilst teaching over a wide range of aspects of fibre reinforced polymers and administrating our Masters course. He is world leading in fractographic analysis of polymer composites, for which he has written the seminal book on the field, and regularly undertakes in-service investigations in support of industry. He is also world leading in the development of multifunctional materials.

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Dr Robert Hewson

Reader in Aircraft Design

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Dr Hewson's research includes multiscale methods and design optimisation. He supervises a number of PhD students in collaboration with Airbus UK in the field of multiscale design optimisation and has a Royal Academy of Engineering Industrial Fellowship. The response surface methods developed and free material optimisation approaches used have a number of applications in composite structural design where fibre angle or lamination parameters replace the more typical pseudo-density encountered in topology optimisation methods.

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Professor Lorenzo Iannucci

Professor of Advanced Structural Design

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Prof Iannucci's major interests continue from research conducted in industry prior to Imperial, including leading one of the first EU projects on composite damage modelling in 1988. On joining the department his interests in the development of modelling techniques for a wide range of advanced composites, including Dyneema, Vectran, systems etc. have continued, especially when subject to severe loadings. A family of high rate test equipment has also been developed to allow detailed characterisation of composites while under high rate loadings.

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Professor Tony Kinloch

Professor of Adhesion

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Prof Kinloch holds a personal chair as 'Professor of Adhesion'. He has published over two hundred patents and refereed papers in the areas of adhesion and adhesives, toughened polymers, nanocomposites and the fracture of polymers and fibre-composites; and written and edited seven books in these areas.

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Dr Mirko Kovac

Reader in Aerial Robotics

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Dr Kovac is the Director of the Aerial Robotics Laboratory, focussing on the development of novel, biologically inspired flying robots for distributed sensing in air and water and on autonomous robotic construction for future cities. Dr Kovac's particular specialisation is in robot design, hardware development and multi-modal robot mobility. Previously he was post-doctoral researcher at the Harvard Microrobotics Laboratory as part of the Wyss Institute for Biologically Inspired Engineering at Harvard University in Cambridge, USA.

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Dr Koon-Yang Lee

Senior Lecturer in Composite Manufacture

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Dr Lee's research focuses on the development and manufacturing of novel polymeric materials with a focus on tailoring the interface between multiple phases to bridge the gap between chemistry, materials science and engineering. He has a particular focus on cellulose and nanocellulose engineering; design and fabrication of renewable polymer composites; surface and interface engineering to improve polymer (nano)composites; life-cycle assessment of composite materials; particle-stabilised emulsions and foams; novel manufacturing for polymer foams and recycling of waste materials.

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Dr Qianqian Li

Lecturer in Composites

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Dr Li has 10 years' experience leading research in composite manufacturing, process optimisation and product analysis. She has proven track record on both metal and polymer composite development. Her primary research interests in lightweight composite fabrication, especially reinforced with nanoparticles. Other interests include the dispersion of nanoparticles in different matrices and advanced manufacturing processes such as additive manufacturing.

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Dr Nan Li

Lecturer in Lightweight Design & Manufacturing

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Dr Li's research addresses the development of breakthrough technologies to manufacture and design high-performance lightweight vehicles for a more environmentally-friendly footprint. Her main research focuses are innovative manufacturing process development for lightweight structures (e.g. forming Fibre Reinforced Thermoplastics sheets); lightweight structural design and optimisation; and design-led-manufacturing modelling.

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Dr Luke A. Louca

Reader in Engineering Structures

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Dr Louca's principal research interests, where he has published some 40 papers in leading journals and conferences, lie in the area of behaviour and design of structures subjected to explosions. Much of this has focussed on steel structures for offshore applications but is currently actively engaged in both civil and defence applications using both traditional construction materials and fibre reinforced composite structures.

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Mr Joseph Meggyesi

Mechanical Testing Laboratory Supervisor

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Mr Meggyesi has nearly 40 years' experience in engineering. Joining the Aeronautics department in 1988, he has worked for the centre for approximately 15 years. He manages the centre's testing facilities, his duties including overseeing Health & Safety, training on the facilities, technical consultations with staff/students, equipment & software updates, calibrations, servicing, and general laboratory management.

Professor Rafael Palacios

Professor in Computational Aeroelasticity

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Prof Palacios's research is concerned with shaping aeroelastic behaviour in the dynamic interactions between deforming structures, the surrounding fluid, and feedback control systems. We develop computational models for dynamic and performance predictions and use them to investigate aeroelastic tailoring (changing composite layup to shape the aeroelastic behaviour), simultaneous layout and shape optimization, and feedback control (through discrete surfaces and integral actuation) to optimize performance of flexible air vehicles and offshore wind turbines in adverse conditions.

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Dr Ajit Panesar

Lecturer in Design for Innovative Manufacturing

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Dr Panesar has more than 10 years' experience in applying computer methods to progress innovative manufacturing technologies such as additive manufacture (AM) and composite tow steering. The core of his research has been the use and development of optimisation algorithms and numerical methods, to establish a framework for novel design tools that exploit the opportunities offered by these promising technologies. His interests include: topology optimisation & lattice structures; variable stiffness composites and multifunctional design optimisation.

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Dr Joaquim Peiro

Reader in Aerodynamics

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Dr Peiro focusses on the development of a methodology of the CFD simulation of moulding processes. This methodology has been successfully applied to the modelling of the RTM (resin transfer moulding) processes employed in the manufacturing of propeller blades and the quantitative evaluation of mould filling times for realistic geometries. This interest extends to processing of viscous polymers such as thermoplastics.

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Dr Soraia Pimenta

Lecturer in Mechanical Engineering

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Dr Pimenta's contributions to the field of Composites fall under two main umbrellas: (i) developing original, accurate and efficient models for the mechanical response of composites, and (ii) promoting a new generation of manufacturable, damage tolerant and sustainable composites. She has contributed to the state of the art on a wide-range of composites (virgin & recycled, continuous & discontinuous) using a combination of experimental, analytical and numerical techniques, applied to composites at the micro-, meso- and macro- scales.

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Professor Silvestre Taveira Pinho

Professor in the Mechanics of Composites

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Prof Pinho's expertise includes; experimentally isolating failure modes in composites, and then simulating them using analytical models; developing numerical models to represent failure; measuring the energy associated with translaminar fracture and, developing more damage-tolerant composites via engineering their microstructures. He won an international benchmark on failure prediction for composite materials in the 2nd World-Wide Failure Exercise. His models are commercialised worldwide (e.g. Abaqus and LS-Dyna), and custom models are used by different institutions.

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Professor Paul Robinson

Professor of Composites,
Head of Department of Aeronautics

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Prof Robinson's research interests include susceptibility of composites to delamination, development of tests for characterising delamination resistance and methods for predicting delamination development due to static, impact and fatigue loading. More recently his research has included investigation of ductile composite architectures, morphing structures, and controllable stiffness and shape memory composites.
He is also a co-I on the Clean Sky 2 project "Structural Health Monitoring, Manufacturing and Repair Technologies for Life Management of Composite Fuselage" (SHERLOC).

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Professor Eduardo Saiz Gutierrez

Professor of Structural Ceramics

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Prof Saiz's research interests include development of new processing techniques for the fabrication of ceramic-based composites, in particular hierarchical composites with bioinspired architectures, the study of high temperature interfacial phenomena such as spreading, the fabrication of graphene-based structures and composites and the development of new materials to support bone tissue engineering. He is the director of the Centre for Advanced Structural Ceramics. He is the coordinator of BioBone, an ITN in the field of bioceramics.

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Dr Matthew Santer

Senior Lecturer in Structures

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Dr Santer has carried out research into the behaviour of high strain composite (HSC) flexures for deployable space structures, characterising and modelling their deployment mechanisms. Using thin ply laminates, self-deploying self-locking flexures have been investigated and developed. This work has been funded by the US Air Force Research Labs, Airbus Defence and Space, and DSTL.

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Professor Milo Shaffer

Professor of Materials Chemistry

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Prof Shaffer has extensive experience of carbon and inorganic nanomaterials synthesis, modification, characterisation, and application, particularly for nanocomposite and hierarchical systems. Notable recent work includes new, patented methods for the dispersion, surface functionalisation and characterisation of carbon nanomaterials, and new approaches to the synthesis of functionalised oxide nanoparticles in situ. Exploitation of nanomaterials is limited by difficulties in synthesis and processing, and his research focuses on these problems.

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Dr Zahra Sharif Khodaei

Senior Lecturer in Aerostructures

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Dr Sharif Khodaei's main area of research is structural integrity and health monitoring with particular focus on damage detection and characterization in composite structures based on permanently mounted sensors on the structure. She has been involved in several EU projects (SMASH, SCOPE, SARISTU, SHERLOC) as part of FP7 and CleanSky funding scheme were methodologies and technologies for maintenance and repair of composite structure have been developed and tested based on building block approach.

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Dr Siti Rosminah Shamsuddin

Teaching Fellow in Aeronautics

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Prior to joining the department, Dr Shamsuddin was a Post-Doctoral Research Associate in Polymer and Composite Engineering (PaCE) Group, Department of Chemical Engineering from June 2012 until June 2016. Her research interests include manufacturing and characterisation of high performance fibre reinforced polymer composites and nanocomposites as well as interfaces in composite materials.

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Dr Qilei Song

Lecturer in Chemical Engineering

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Dr Song has research interests in design, synthesis, and characterisation of functional polymers and nanoporous materials for applications in membrane separations, adsorption, catalysis, and energy conversion and storage. He has worked on several types of cutting-edge microporous materials and their applications in membranes for gas separations, notably metal-organic frameworks (MOFs) and polymer/MOF composites, polymers of intrinsic microporosity and novel porous molecular materials known as porous organic cages. He has worked on microporous polymer nanofilm membranes.

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Dr Vito Tagarielli

Reader in Mechanics of Solids

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Dr Tagarielli has a passion for mechanics of solids and applied mechanics. His main contributions to research have focused on: measuring, modelling and optimizing the dynamic response of monolithic and sandwich composites to intense dynamic loading; fluid-structure interaction during blast; new experimental methods at high strain rates; the electro-mechanical response of conductive CNT-polymer composites; stochastic modelling of composites and investigating size dependence and intrinsic uncertainty of the mechanical response of these materials.

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Dr Ambrose Taylor

Reader in Materials Engineering

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Dr Taylor is the leader of the 'Nanomaterials' group which specialises in the characterisation and modelling of particle-modified thermoset polymers. He has researched the impact and durability performance of rubber-toughened structural epoxy adhesives, and predicted the lifetime of adhesive joints in fatigue. He is investigating the structure/property relationship of thermoset/inorganic hybrids. He also has interests in using other nanomodifiers (e.g. layered silicates, carbon nanotubes and silica nanoparticles) as tougheners for thermosets.

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Facilities

▲ *Our high specification autoclave means we can manufacture large composite components.*

For research, modelling, testing and training in advanced composites

The Composites Centre has world-leading facilities for composite synthesis, manufacture, characterisation and testing, and these underpin the internationally renowned research we undertake in this field. These facilities are staffed by a team of research technicians with considerable experience in supporting research into composite materials and structures.

▶ *Waterjet cutting of short fibre composites.*

▶ *For fabrication of multifunctional materials we have a furnace which is used to pyrolise materials under an inert atmosphere.*

Materials Synthesis and Multifunctional Materials Laboratories

Developing new constituents and their resulting composites is a key strength of the Composites Centre, and we have two laboratories that are dedicated to the formulation of new and multifunctional materials. In the Materials Synthesis laboratory we have facilities associated with formulating, developing and characterising natural composites, such as nanocellulose based materials. In this laboratory we also have facilities for the fabrication of nanoreinforced metal matrix composites. Whilst in the Multifunctional Materials laboratory we have facilities for the synthesis of carbon aerogel (CAG) reinforced carbon fibre lamina, equipment to assemble structural power devices in a moisture and oxygen free environment and a potentiostat with which to characterise their electrical performance.

RESEARCH FACILITIES

» **Fabrication of natural composites and their constituents**
We have an injection moulder, twin-screw extruder, hydraulic hot press, large volume centrifuge (1.5 L), -60° C freeze dryer, automatic film applicator and a colloid mill. For the subsequent characterisation of these natural materials we have a Gurley densometer, helium pycometer, tensiometer and a microtensile tester with a 200 N load cell.

» **Fabrication of metal matrix nanocomposites**
We have a unique 'melt stirring furnace' with a controlled gas atmosphere. The temperature can be raised to 1100° C whilst applying either stirring or ultrasound to the metal melt. It is a tube furnace with two open ends such that different devices or instrumentation can be attached from both sides. It is also equipped with a HEPA filter for safely producing nanoparticle reinforced composites.

» **Development of structural power materials**
We have a double walk-in fumehood and ovens in which to infuse and age the CAG precursors, and a Lenton (ECF 12/45) 42 litre furnace with a maximum temperature of 1200° C to pyrolise the CAGed lamina under an inert atmosphere. We have a Braun glovebox with an argon atmosphere in which to assemble the structural supercapacitors, and an EC Lab SP-240 potentiostat with which to characterise the resulting devices.

POINT OF CONTACTS

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▼ *With a maximum temperature of 400° C, our custom made hydraulic press can not only be used to press mould and cure thermoset materials but also process high performance thermoplastics.*

Composite Manufacturing Suite

For the assembly and manufacture of conventional composite systems we have a very well-equipped Composite Manufacturing Suite. We can assemble and laminate both thermoplastic and thermoset based fibre reinforced composites, either via liquid resin infusion methods or as prepregs. We can cut of all types of dry fabrics and prepreg tapes precisely and to bespoke shapes using our conveyor belt ply cutter. We have a large capacity autoclave to cure thermosets and a heated press with which to process thermoplastic composites. For out-of-autoclave routes we have liquid resin infusion and diaphragm/thermoforming capabilities. We have facilities for filament winding and micro-braiding, and finally we have the capability to 3D print using composite feedstocks.

For composite finishing we have comprehensive facilities for both wet and dry cutting, drilling, abrading and grinding of composites, including a waterjet cutter and facilities for high precision CNC cutting of composite components. Finally, we have facilities for composite repair.

It should be noted that we have put facilities in place, such as HEPA filters, such that we can process and finish nanoreinforced materials safely.

RESEARCH FACILITIES

» **Fabrication of composites**
For the cutting of dry fabrics and prepregs we have a conveyor belt cutter with an accuracy of ±0.1 mm and maximum cutting width of 1524 mm. These materials can then be fabricated in to composites using our 1 m diameter autoclave with a maximum temperature and pressure of 450° C and 28 bar respectively. Alternatively we have a heated press with a platen size of 500 mm x 500 mm, and a maximum pressure and temperature of 400 kN and 400° C, respectively.

» **Out-of-autoclave processes**
We have liquid resin infusion facilities and diaphragm/thermoforming using equipment which can accommodate laminates 1450 mm x 1150 mm in size at up to 250° C. For filament winding we have a robot system which can control mandrel rotation, material supply rate and filament tension. For micro-braiding we have a Maypole-type machine with two working heads, providing varying combinations of up to sixteen carriers and eight horn gears at 30 m/h, permitting combinations of different yarns in a single braid and over-braiding of longitudinal yarns. Finally, for 3D printing of composites we have Markforged 3D printers with continuous carbon, glass or Kevlar fibres in a nylon matrix. This has maximum printing dimensions of 320 x 132 x 160 mm.

» **Composite finishing**
We have a full suite of facilities including a waterjet cutter with a maximum cutting size of 1.2 m x 1.0 m which can cut up to 10 m/min to an accuracy of ±0.07 mm. For dry cutting we have circular (182 mm diameter) and band saws, a Murg 24BB diamond wire cutter and a Minicut 40 precision minicutter, as well as an Axiom CNC Router with a machining envelope of 610 mm x 610 mm x 153 mm.

» **Composite patch repair**
We have the LESLIE GMICRT 9201 Kit that provides the tools to prepare the surface of composites to conduct repairs. This enables us to apply different repair strategies such as scarf or step-sanded repair on flat or curved composite panels.

» **Out-of-autoclave or on the field repair applications**
The portable smart bonding console ANITA EZ09 can cure repairs with its heating blanket and vacuum bags.

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◀ *We have specialised equipment to perform research on repairs of advanced composite structures.*

Composite Characterisation

We have an extensive range of facilities for characterisation of composite materials and structures. This includes non-destructive capabilities (ultrasonic and x-radiography), and vacuum and environmental conditioning ovens. We have capabilities for physical characterisation of composites and their constituents, including a Differential Scanning Calorimeter (DSC) and a Dynamical Mechanical Thermal Analyser (DMTA) to measure glass transitions, crystallisation, phase changes and cure kinetics. Finally, within the Composites Centre, we have a suite of optical and electron microscopes (with an in-situ testing capability), and the associated preparation facilities.

RESEARCH FACILITIES

» **Ultrasonic inspection**
We have an immersion tank system (1700 mm x 1300 mm x 500 mm) with a maximum scanning speed of 500 mm/s, with 1 MHz to 15 MHz probes. We also have a portable DolphiCam system which permits handheld inspection of components of up to 8 mm thick. We have a digital X-ray inspection system with an energy range of 10 kV to 100 kV, with a maximum sample size of 350 mm x 430 mm, giving a resolution of 5 – 45 μm. For environmental conditioning we have vacuum ovens and 100 litre conditioning chambers (TAS Thermal Vacuum and BINDER GmbH KMF 115) with a temperature range from -70° C to 180° C, with controllable humidities from 10 to 98%, pressure ranges from ambient to 185 kPa and vacuum ranges of ambient to -2 kPa, permitting programmable heating and cooling ramps.

» **Physical characterisation**
We have TA Instruments Discovery (DSC and TGA) and RSA-G2 solid rheometer (DMTA). The former has a 50 position autosampler with a temperature range -90° C to 725° C whilst the latter has a 35N loadcell and can test over -155° C to 600° C under tensile, 3 point bending, single or double cantilever and compression.

» **Microscopy**
We have an Olympus SZX7 and a Leica M125 microscopes with a VisLED illumination system using either brightfield or darkfield illumination. For metallographic inspection of composites we have a dedicated set of grinders and polishing wheels used exclusively for polymeric composites, and a Zeiss Axio Imager. M2m optical microscope with a wide selection of contrast enhancement devices. Finally, we have a Hitachi S-3700N Scanning Electron Microscope with a large chamber (110 mm x 110 mm x 50 mm sample size). This has the capability to do in-situ mechanical testing using a Deben MY10383 stage with a 50 mm stroke and either a 150 N or 5 kN loadcell.

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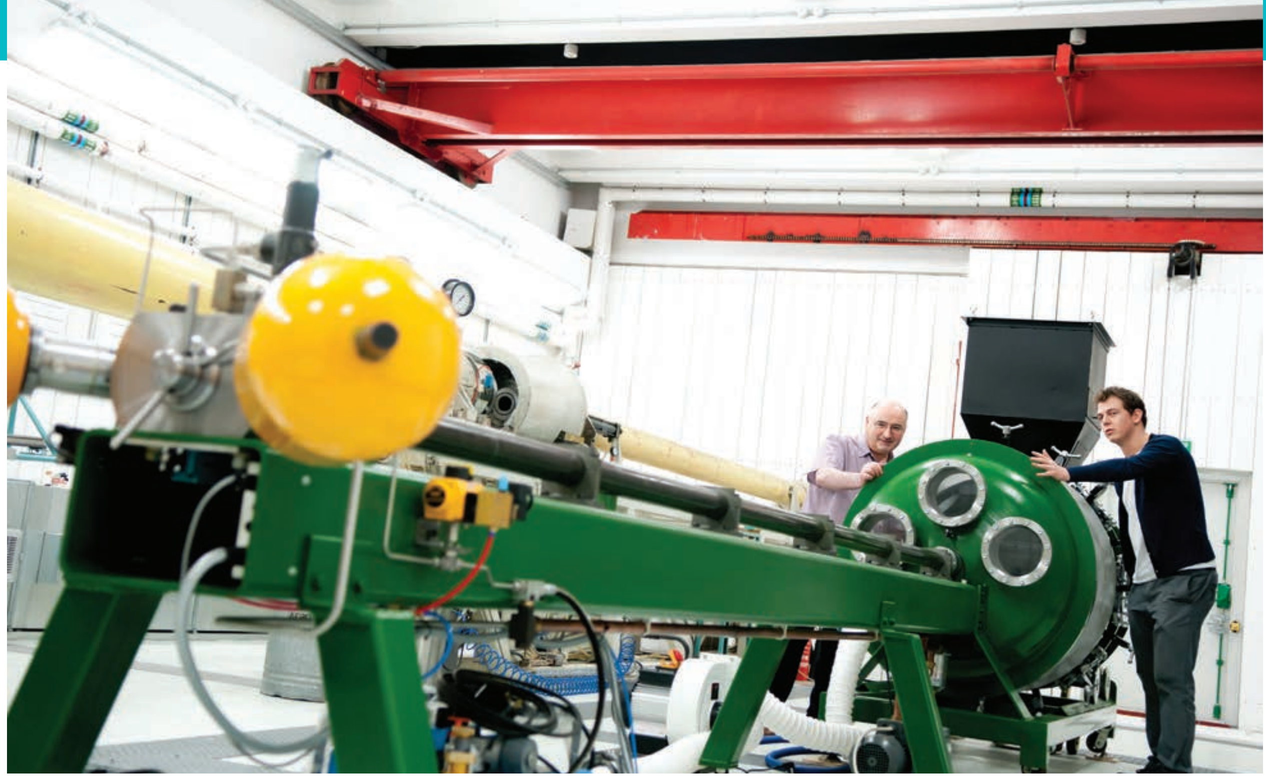
▲ *Our conveyor belt cutter permits automatic, precise cutting of all types of dry fabrics and prepreg tapes.*
▲ *For characterisation of polymeric materials we have a Differential Scanning Calorimetry (DSC).*
▲ *Our autoclave is able to process almost any thermoset and thermoplastic material.*



▲ *50 mm single stage gas gun which can fire projectiles between 10–250 g to 60–1400 m/s.*
▲ *Instron 25kN hydraulic universal test machine is capable of single shot or fatigue testing.*

Mechanical Testing

The Composites Centre has considerable and extensive experience in mechanical testing of composite materials and components. Hence we have an extensive range of mechanical test machines to undertake quasi-static, fatigue and dynamic conditions under loading ranging from 10 N to 2500 kN. We also have specialised capabilities such as a linear motor test frame which can undertake biaxial (tension/torsion) tests. We are able to undertake impact testing over a range of velocities, including a drop weight impactor with a bespoke impact under load capability, as well as gas guns and Hopkinson bars. Most of our test machines can accommodate environmental chambers to permit hot or cold testing. We have the full range of standard (ISO and ASTM) test fixtures for composite testing, but also have the capability and substantial experience in the design and manufacture of bespoke test fixtures. We have access to a range of instrumentation techniques (both contact and non-contact) with which to capture test information. Finally, we have containment facilities in place with which to test nanoreinforced composites.

RESEARCH FACILITIES

INSTRON MECHANICAL TEST MACHINES

We have a comprehensive suite of Instron mechanical test machines with advanced Instron 8800 controllers for dynamic machines using Wavematrix and BlueHill software for static machines. We have two conventional screw driven 50 kN machines with a range of load cells down to 10 N and a 250kN frame with hydraulic grips.

» **Higher quasi-static and fatigue loading**
we have servo-hydraulic machines with hydraulic grips with capacities of 100 kN (100 mm stroke) and 250 kN (250 mm stroke). Our largest capacity machines is a 2500 kN hyperstiff screw driven machine capable of accommodating 1.5 m x 1.2 m panels with a maximum loading rate of 2 mm/min. For higher rate loading we have a 25 kN frame (250 mm stroke) capable of 3 m/s with WaveMatrix dynamic testing software. Finally, we have a 10 kN (7 kN static) Instron Electropuls linear motor dynamic test machine with torsion (100 Nm) capability, capable of 60 mm stroke at 1.7 m/s. Most of these machines can accommodate our environmental chambers capable of testing over -150 to +350° C.

» **Impact testing of composites**
We have an Instron/Ceast with a maximum mass and velocity of 70 kg and 24 m/s, giving a maximum energy of 1800 J. This has an associated environmental chamber such that impacts can be conducted at -70° C to 150° C. The impactor can be used in conjunction with a bespoke compression frame capable of loading panels up to 1.2 m x 1.0 m in size to -1500 kN. We also have a medium velocity (crossbow) impactor to simulate runway debris up to 65 m/s.

SINGLE STAGE GAS GUN

The department has a 50 mm single stage gas gun which can fire projectiles between 10-250 g to 60-1400 m/s. The system fires into a vacuum chamber of 940 mm diameter which accommodates large test panels. It has a unique catching system to allow ice and other debris to be fired. The single stage gas gun can be converted into a two stage light gas gun which can fire projectile masses 1-10 g between 1-4000 m/s. A smaller single stage gas gun is also available. It is 25 mm bore and can fire projectiles of up to 10 g at a maximum speed of 500 m/s. It fires into a chamber which accommodates test panels that are typically 150 x 100 mm. The chambers of both guns both have viewing windows to enable the use of high speed cameras.

HOPKINSON BARS

The Department also has a micro and conventional tensile Hopkinson bars for high rate characterisation of composites. A compression Hopkinson bar for the detailed characterisation of the compressive behaviour of composites is also available; this can be fitted with a newly developed apparatus to allow high strain rate tensile testing of composites, ceramics, as well as dry fibres, yarns and tapes used in composite manufacturing.

TEST INSTRUMENTATION

Finally, we have a range of test instrumentation associated including strain gauge amplifiers; clip on extensometers; high speed digital oscilloscopes: three Imetrum Optical Strain systems with a range of lenses; a GOM DIC (Digital Image Correlation) system; a Mistras Acoustic Emission system; two Vision Research V12.1 High speed Cameras and a Vision Research 25.1 camera with FAST option (1 million fps).

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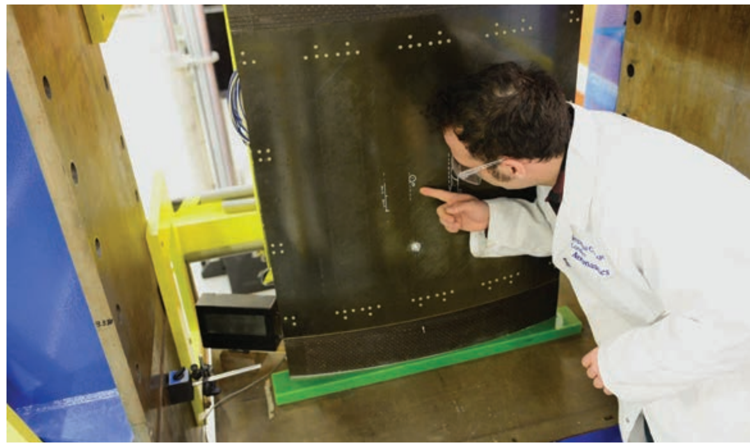

▶ *Hyper stiff compression test machine, particularly designed for testing of stiffened panels and large composite structures.*
▶ *Drop weight impactor for impacting composites components whilst under compressive load.*

▲ *Olympus stereo optical microscope.*

Microscopy Suite

The Department of Materials is affiliated to the Composites Centre and has a wide range of facilities for characterising and imaging composite materials. This includes two atomic force microscopes; a Bruker Innova for routine analysis using standard tapping and contact modes, whilst the Asylum MFP-3D classic can also investigate electrical (KPFM), magnetic (MFM), piezoelectric (PFM) and nanomechanical properties (force mapping and AM-FM).

We also have the Harvey Flowers suite of electron microscopes, which includes three scanning electron microscopes (SEMs) and three transmission electron microscopes (TEMs), the latest being the state-of-the-art monochromated FEI TITAN 80/300 and FEI Helios NanoLab 600 DualBeam. In addition, the dedicated microscopy team maintain the latest technology in the two sample preparation labs and data processing suite.

POINT OF CONTACT

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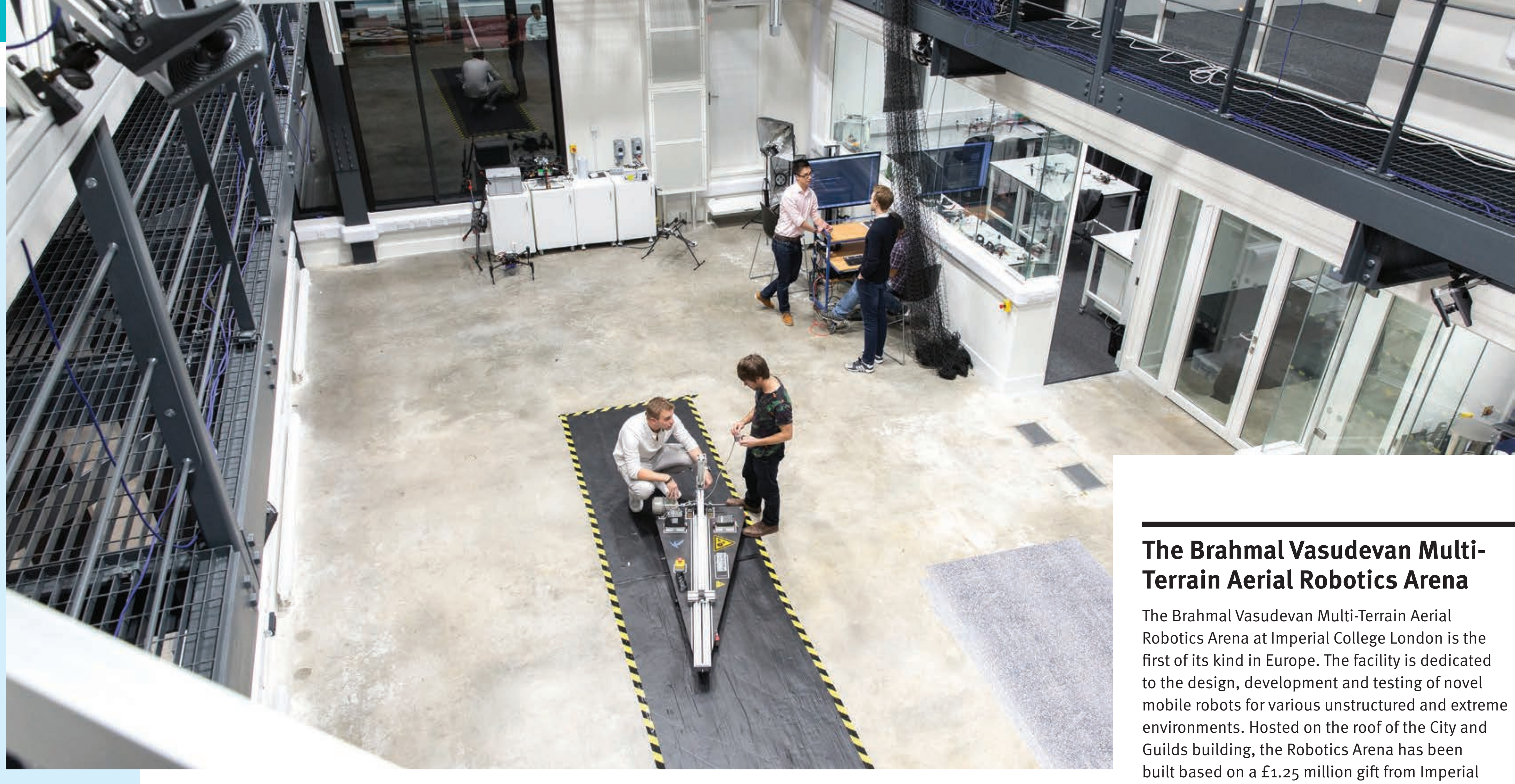

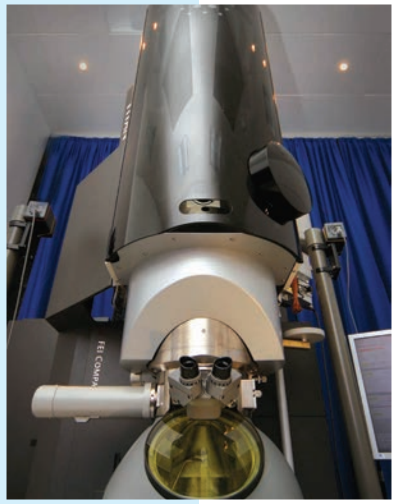

▲ *Zeiss optical microscope.*
◀ *The UK's first FEI Titan 300-80 S/TEM microscope.*

▲ *The Brahmal Vasudevan Multi Terrain Aerial Robotics Arena Read is the first of its kind in Europe, enabling engineers to test the next generation of aerial robotics for urban environments and extreme conditions.*
▲ *The researchers in the arena can simulate different terrains in the air, the ocean and on land.*

The Brahmal Vasudevan Multi-Terrain Aerial Robotics Arena

The Brahmal Vasudevan Multi-Terrain Aerial Robotics Arena at Imperial College London is the first of its kind in Europe. The facility is dedicated to the design, development and testing of novel mobile robots for various unstructured and extreme environments. Hosted on the roof of the City and Guilds building, the Robotics Arena has been built based on a £1.25 million gift from Imperial alumnus Mr Brahmal Vasudevan, who graduated in Aeronautical Engineering in 1990.

The facility includes one Innovation Room for work group creative design and robot development. Located next to it is the Robotics Workshop containing 3D printers, micro-manufacturing equipment and a fume hood for component fabrication and assembly. Two outdoor spaces are accessible from the arena for open-air testing.

The arena can be configured for various terrains, including air/ground/water and it allows for the setup of simulated challenging environments, industrial scenarios and urban infrastructures. It is designed to allow for experiments including smoke and combustion and it is fully laser rated. The space is equipped with sixteen high speed 3D aerial tracking cameras, that can be used to record in real-time the dynamics of robots in air and on ground. A further ten 3D tracking cameras are positioned in a water tank, used to test novel multi-terrain robots that can move in both air and water.

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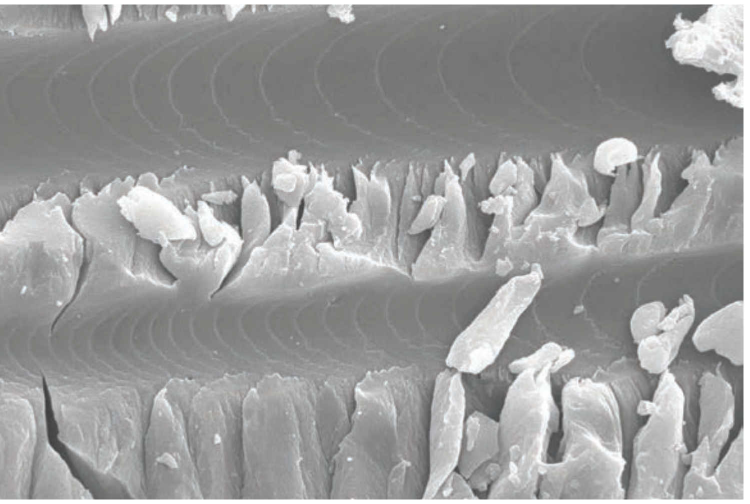
Collaborations

Explore the mechanisms by which you can interact or collaborate with the Composites Centre ➜

UNDERGRADUATE (MENG) PROJECTS

Final year undergraduate students undertake a research project which usually runs for a period of months in the Spring/Summer term (dependent on the department of study). We canvas for projects in the late Summer/early Autumn and provide the list to the students from which they select and rank their potential projects. Once assigned to the student, the project scope can be modified based on discussions between the student, his internal supervisor and the host organisation. The student is not paid for the duration of such a project, but should be provided with access to facilities to undertake the research at the host organisation. The host should assign the student an external supervisor who will provide day to day guidance and will provide an assessment at the end of the project. If needs be, the project can be confidential and NDAs can be arranged to protect IP. This is a good mechanism for exploring a short piece of research with relatively little financial outlay.

▼ *Fatigue striations in aerospace composite components.*



MASTERS (MSC) PROJECTS

The Aeronautics Department run three MSc courses, the details of which are given at: www.imperial.ac.uk/aeronautics/study/pg. As with undergraduate projects, we canvas for projects in the late Summer (August/September) and provide the list to the students from which they select and rank their potential projects. The project runs from May until September, and once assigned to the student, the project scope can be modified based on discussions between the student, their internal supervisor and the host organisation. For the Composite MSc, it is important that the project is clearly utilising the composite knowledge the student has developed during their MSc course. The student is not paid for the duration of such a project, but should be provided with access to facilities to undertake the research at the host organisation. The host should assign the student an external supervisor who will provide day to day guidance and will provide an assessment at the end of the project. If needs be, the project can be confidential and NDAs can be arranged to protect IP. As with undergraduate projects, this is a good mechanism for exploring a short piece of research with relatively little financial outlay.

POSTGRADUATE PROJECTS (PHD STUDENTSHIPS)

There are opportunities for industrial partners to support postgraduate students, covering their fees, stipend and costs for materials, facilities, etc. Such a mechanism will allow you to dictate the research direction and provide greater control of the intellectual property and knowledge generated from the research. The best means to initiate such projects is through direct contact with the relevant academic, who can formulate and cost such a research project. Furthermore, there are some opportunities for industrial CASE awards for PhD positions, as detailed at: https://epsrc.ukri.org/skills/students/coll/icase.

RESEARCH COLLABORATIONS

There are opportunities for industrial partners to steer and advise on research council funded research, and provide in-kind support through committing your staff time to advisory and progress meetings. Cash contributions or industrial facility access are also welcomed as a form of support to steer such projects. Alternatively, secondments to your organisation, or vice-versa, may also be valuable. To initiate such a collaboration mechanism it is best to approach the relevant academic.

INNOVATION COLLABORATIONS

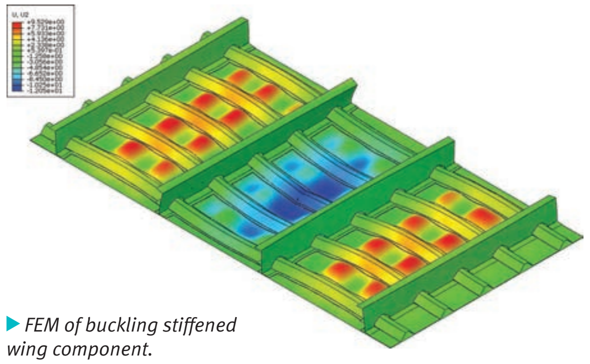
Much of our research is focussed at the TRL0 to TRL3 level, and we welcome opportunities to translate and mature our research into real-world applications. The Composites Centre has a good track record in accessing funding from organisations such as ATI and Innovate UK. For large grants the associated Department within the Composites Centre may be able to supplement the research by funding PhD studentships to complement the research. To initiate such a collaboration mechanism it is best to approach the relevant academic.

H2020 COLLABORATIONS

The Composites Centre has a very strong track record in formulating, leading and securing European Union funding, and there are numerous mechanisms by which we can collaborate with industry via this route. Further details of these mechanisms can be found at https://ec.europa.eu/programmes/horizon2020/en/what-work-programme. Imperial has a dedicated European Office which can advise on applying for, structuring and managing such projects. To initiate such a collaboration mechanism it is best to approach the relevant academic.

DONATIONS AND SCHOLARSHIPS

An alternative route to support the research is via philanthropy to support the next generation of composite engineers, help sustain academic excellence and develop frontier research areas. The Centre would be delighted to discuss priority areas including scholarships and flexible support funds. Please discuss this further with the Head of the Composites Centre or relevant academics.



▶ *FEM of buckling stiffened wing component.*

CONSULTANCY

The academics in the Composites Centre have considerable experience and expertise which can be utilised to address your industrial challenges, near-term development problems and litigation/expert witness roles. Such consultancy is managed by Imperial Consultants who should be approached, along with the relevant academic, to initiate such work.

FACILITIES

The Composites Centre has a wide range of facilities for composite manufacture, characterisation and testing, with skilled technicians who can undertake the work. To initiate such work the Composite Suite Manager (Dr Frank Gommer) should be approached.

GUEST LECTURING

We are keen to expose our students and researchers to an industrial perspective and outlook on composites, and would welcome guest lecturers from research providers, industry and government organisations. Please contact the Head of the Composites Centre if you are interested in delivering a lecture.

▼ *Our furnace for making CNT reinforced light alloys.*

Contact us

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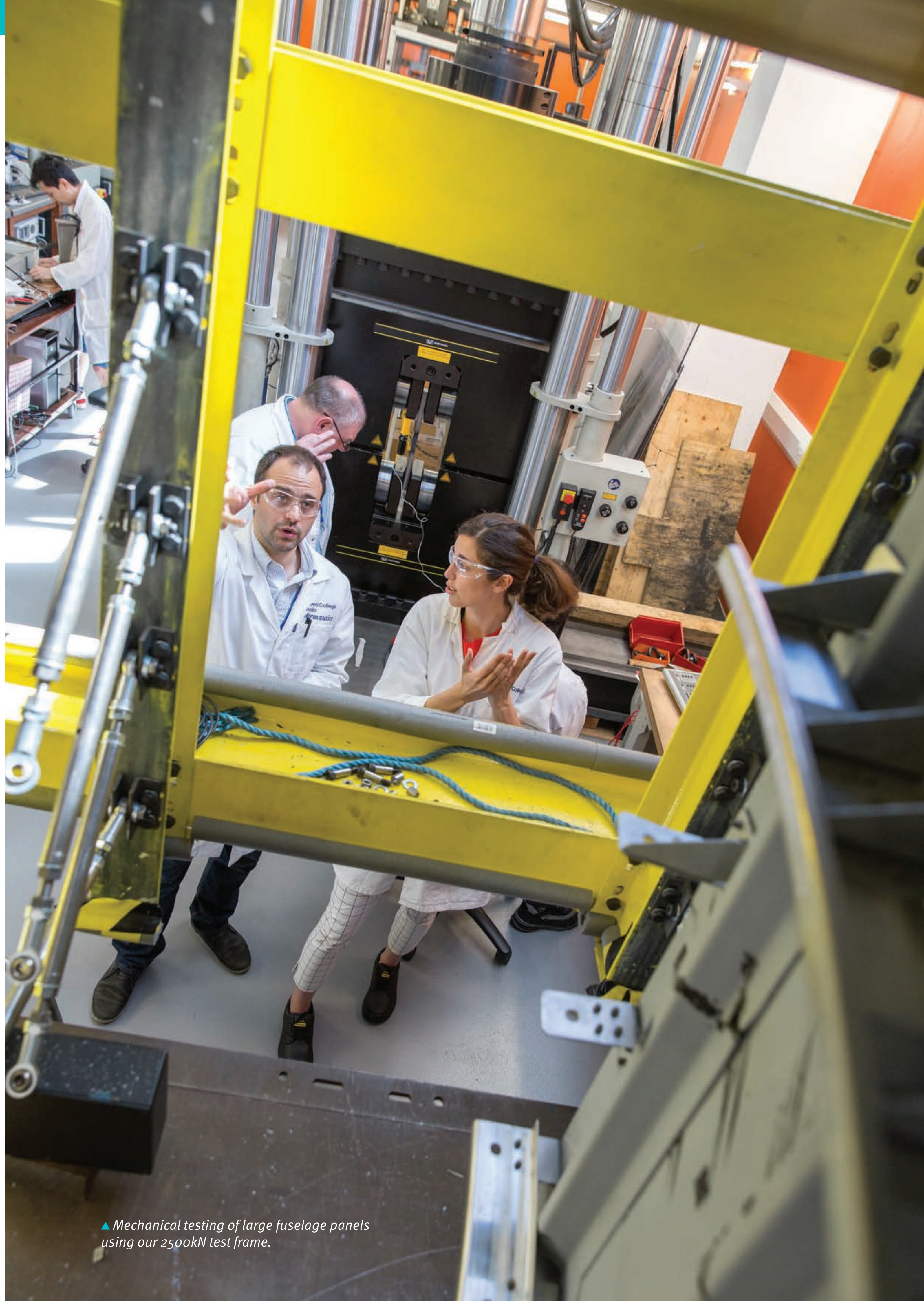
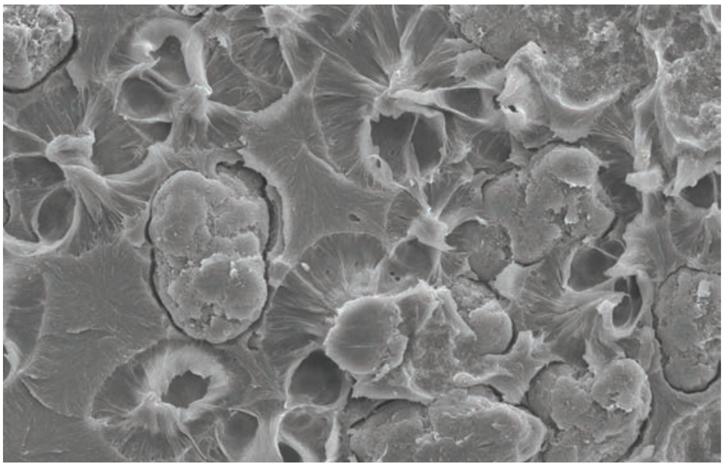


Mechanical testing of large fuselage panels using our 2500kN test frame.

» www.imperial.ac.uk/composites-centre | @CompositeCentre

▲ *We are developing methods for in-service repair of composite components.*



▲ *Fractographic investigation into highly toughened composite components for industry.*