Bristol Composites Institute Launch and ACCIS 10th Anniversary Conference

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Queen's Building, University of Bristol
Nonlinear ultrasonic detection of kissing bonds in composite structures
Jonathan Alston, Anthony Croxford, Jack Potter

Adaptive air inlet for fluid control
Gaetano Arena, Rainer Groh, Raf Theunissen, Paul Weaver, Alberto Pirrera

Graded composite by spatial distribution of additives for inductive heating in repair
Giampaolo Ariu, Ian Hamerton, Bhrami Jegatheeswaram Pillai, Dmitry Ivanov

Consolidation-driven defect generation in severely tapered laminates
Jonathan Belnoue, Oliver Nixon-Pearson, Dmitry Ivanov, Kevin Potter, Stephen Hallett

Development of improved fibre reinforced feedstocks for high performance 3D printing
Lourens Blok, Ben Woods, Marco Longana, HaNa Yu, Kevin Potter

Development of through-thickness reinforcement (TTR) architectures to achieve effective delamination management and tailored mechanical performance
Alex Cochrane, Stephen Hallett, James Lander

Actively cooled composites via embedded vascular networks
Jim Cole, Ian Bond, Andrew Lawrie

Dome-Shaped PLA Auxetic Cellular Honeycombs
Yousef Dobah, Sixtine Michel, Fabrizio Scarpa, Anton Shterenlikht

Multi-scale modelling of complex composite structures
Bassam El Said, Stephen Hallett

Collaborative Human-Robot layup
Michael Elkington, Nikita Ghandi, Mark Libby, Andrew Kirby, Carwyn Ward

Notch insensitive pseudo-ductile quasi-isotropic thin-ply carbon/glass hybrid composites
Mohamad Fotouhi, Meisam Jalalvand, Michael Wisnom

Demonstrating the potential for pseudo-ductility in structural components: simulation and testing
Jonathan Fuller, Meisam Jalalvand, Michael Wisnom

Examining the influence of graphene species on toughening mechanisms in industrially relevant epoxy resins
Ian Gent, Napatsorn Prakobboon, Liam Robinson, Cristina Vallés, Rainer Kuusvek, Robert J Young, Ian Kinloch, Ian Hamerton

3D Stress interaction for composites failure
Kilian Grübler, Michael Wisnom, Stephen Hallett

Efficient models for nonlinear dynamic analysis of thick composite laminates
Aewis Hii, Luiz Kawashita, Alberto Pirrera, Stephen Hallett

Novel interfaces in hybrid composite-metal struts
Jordan Jones, Luiz Kawashita, Byung Chul Kim, Stephen Hallett

Further experimental characterisation of defects and features
Mike Jones, Hafiz Ali, Luiz Kawashita, Stephen Hallett

Effect of high velocity impacts on thin composite plates
Ashwin Kristnama, Michael Wisnom, Stephen Hallett, David Nowell
Combined effects of load reversal and mode ratio on the fatigue behaviour of carbon/epoxy laminates
Rico Kuehlewind, Luiz Kawashita, Stephen Hallett

Structural efficiency via stiffness adaptation
Olivia Leão, Rainer Groh, Alberto Pirrera

Development, Demonstration and Performance Validation of Composite Repair Schemes
Jack Lindley-Start, Luiz Kawashita, Ian Hamerton, Bhrami Jegatheeswaram Pillai

High Performance Discontinuous Fibre Composites: A sustainable route to the next generation of composites
Marco Longana, HaNa Yu, Ian Hamerton, Kevin Potter, Michael Wisnom

Advanced design and manufacturing concept of bend-twist coupled wind turbine blade
Vincent Maes, Terence Macquart, Paul Weaver, Alberto Pirrera

Experimental design of a multiple delamination, mixed-mode fracture test
Yusuf Mahadik, Stephen Hallett

Further experimental characterisation of TTR
Yusuf Mahadik, Hafiz Ali, Stephen Hallett

Large mesh techniques for cohesive zone modelling
Supratik Mukhopadhyay, Stephen Hallett

Multi-scale characterization and modelling of tufted composite structures
Camilla Osmiani, Galal Mohamed, Ivana Partridge

Periodic inclusions in auxetic media
Rita Palumbo, Fabrizio Scarpa, Mohamed Ichchou, Dmitry Ivanov, Olivier Bareille

Static and buckling analysis of composite structures through advanced high-fidelity models
Mayank Patni, Sergio Minera, Paul M. Weaver, Alberto Pirrera

Development of high performance composites by optimising the matrix
Thomas Pozegic, Ian Hamerton, Michael Wisnom

Local grading of composite architectures
Arjun Radhakrishnan, Ian Hamerton, Milo Shaffer, Fabrizio Scarpa, Dmitry Ivanov

Design & manufacture of a composite FishBAC camber morphing device
Andrés Rivero, Paul Weaver, Jonathan Cooper, Benjamin Woods

Novel matrix for GFRP wind turbine blades
Bethany Russell, Carwyn Ward, Shinji Takeda, Ian Hamerton

Numerical modelling of TTR as in-plane defect
Xiaochuan (Ric) Sun, Stephen Hallett

Variable stiffness composite laminates for doubly curved plates using lamination parameters
Matthew Thomas, Paul Weaver, Stephen Hallett

Simulations of graphene nanoribbons for use in polymer composites
Mat Tolladay, Dmitry Ivanov, Neil Allan, Fabrizio Scarpa

Testing and modelling of porosity defects
Iryna Tretiak, Luiz Kawashita, Stephen Hallett
Hybrid reinforced thermoplastic composites
Mario Valverde, Stephen Hallett, Luiz Kawashita, Maik Gude, Robert Kupfer

Fatigue behaviour of CFRP composites under environmental conditions
Georgios Voudouris, Dario Di Maio, Ibrahim Sever

New experiments for in-plane shear characterisation of uncured prepreg
Yi Wang, Dmitry Ivanov, Jonathan Belnoue, James Kratz, BC Eric Kim, Stephen Hallett

Industrial scale nano-reinforced composite structure
Robert Worboys, Ian Hamerton, Stephen Hallett, Rob Backhouse, Luiz Kawashita

Fatigue behaviour of pseudo-ductile thin ply angle-ply carbon fibre laminates
Xun Wu, Jonathan Fuller, Michael Wisnom

Meta-compliance and energy dissipation in cactus-based solids
Ioannis Zampetakis, Alistair Hetherington, Adam Perriman, Fabrizio Scarpa

Advanced modelling techniques of fatigue delamination in composites
Bing Zhang, Luiz Kawashita, Stephen Hallett

Manufacturing of nature inspired composite aircraft designs: CTS (Continuous Tow Shearing)
Evangelos Zympheloudis, Paul Weaver, Kevin Potter, Byung Chul Kim

Bristol-Dresden University Technology Partnership (UTP)
Nonlinear ultrasonic detection of kissing bonds in composite structures

Jonathan Alston, Anthony Croxford, Jack Potter

Kissing bonds are interfaces that are in intimate contact but are not chemically bonded. They can be hard to detect with current ultrasound techniques, but if a strong enough acoustic force is applied by the ultrasound the bond can open up, momentarily reducing the transmission of the interface. This distorts the wave moving energy from the fundamental frequency up into higher harmonics. This work is focused on developing a technique called non-collinear mixing, by measuring the nonlinear response of interfaces for a range of beam interaction angles and frequency combinations. The graphical representation of this data is referred to as ‘fingerprints’ as the features in these fingerprints might allow for kissing bonds, among other interface/material properties to be identified.

(a): Shows the experimental layout. The angles of the input beams and their frequencies are varied. The colour of each pixel in the fingerprints below is related to the intensity of the nonlinearly scattered beam produced by the combination of those two variables.

(b): A kissing bond was approximated by bolting together two aluminium plates. The torque on the bolts can be varied to change the interfacial loading. A solid sample of the same outer dimensions and one with an epoxy resin adhesive bond line were also used.

In the fingerprints below the three different cases can be easily distinguished.

The solid material creates no signal at small interaction angles unlike the other two cases, and the signal is much stronger from the kissing bond than the adhesive bond. There are many subtle features in these fingerprints, too many to be discussed here. The white line indicates the expected solid mixing peak.

To the right are figures showing the effects of altering the interface loading. They were measured at a frequency ratio of 0.9, since most of the interesting features are in the interaction angle parameter space. The furthest right figure is a peak normalised version of the same data. It can be seen that the interface produced the most signal when the bolts were torqued to 10 Nm. Looking at the normalised data, as load was increased the secondary peaks at about 105° and 120° became more prominent. Therefore this technique could be used to both detect kissing bonds and to characterise them.

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Adaptive air inlet for fluid control
Gaetano Arena, Rainer Groh, Raf Theunissen, Paul Weaver & Alberto Pirrera

A design concept for an adaptive, variable geometry fluid inlet is presented. The inlet’s shape adapts passively in response to varying flow conditions. In contrast to traditional designs, the inlet does not rely on separate mechanisms for actuation. Instead, the novelty of the present approach is that a variety of adaptive responses are obtained by exploiting the nonlinear behaviour of post-buckled structures.

Elastic instabilities as an engineering tool of shape adaptation
The geometrically nonlinear elasticity of a representative post-buckled clamped beam is investigated parametrically. The results obtained permit a general understanding of how pre-loading and boundary conditions affect the post-buckling behaviour and its relationship with multistability.

Fluid-Structure Interaction (FSI) simulation
The interaction between the adaptive air inlet, designed exploiting elastic instabilities, and air flow was studied through FSI simulations. Results show that the device can be passively actuated by exploiting the changes in the pressure field caused by air flowing over the curved structure.

Manufacturing of Test Rig for Wind Tunnel (WT) testing
Figure on the left shows the air inlet mechanism in the WT facility (a). One of the composite (1) extremities is clamped to the PMMA plate (3) on the WT floor. Air flows through the. Fig. b, c and d show the mechanism and connected components used to apply vertical displacement and pre-compression to buckle the composite panel and achieve the desired post-buckling behaviour.

WT testing validated FSI results. Figure below shows the inlet in its open and closed states. By increasing air speed, the relative pressure above the structure decreases actuating the snap-through. In the case of a bistable inlet, the closed configuration is held for decreasing air speed. Conversely, monostable inlet snaps back when flow velocity is reduced.

Relationship between pre-compression and velocity at snap-through and snap-back

Applications

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Graded composite by spatial distribution of additives for inductive heating in repair

Giampaolo Ariu, Ian Hamerton, Bhrami Jegatheeswaram Pillai, Dmitry Ivanov

Inductive heating could efficiently supply localised heat, which is essential for composite repair applications. Efficient inductive heating relies on in-plane and through-thickness electrical conductivity of composites. Carbon nanotubes (CNTs) could be used for this purpose, but they need to be carefully positioned within the repair patch to assist cure. This research investigates various methods for spatial positioning of high CNT loadings in composite parts.

Considerations

- Inductive heating = more efficient, localised, and uniform cure of repair patches.
- But: CFRP = low through-thickness electrical conductivity of CFRP, GFRP = no conductivity.
- CNTs could enable inductive heating.
- However, high CNT loadings are needed to provide sufficient conductivity.
- Hence, new methods of CNT integration investigated.

Methodology

A) Magnetic manipulation of functionalised CNTs within resin using DC field;
B) Liquid resin print (localised integration of resin);
C) Hybrid method (combination of both)

Various methods for CNT functionalisation considered

A) Magnetic manipulation of functionalised CNTs within resin using DC field;
B) Liquid resin print (localised integration of resin);
C) Hybrid method (combination of both)

CNT positioning within repair patch

Cobalt distribution progression (magnetically driven CNT migration + filtration):
Migration of Co-plated CNTs manipulated by DC field

Conclusions

- Feasibility of integrating high loading of CNT for effective inductive heating using localised injections is proven;
- Manipulation of CNT position in pure resin and within printed patch using DC field was proven possible;
- It is shown that magnetic positioning of CNT can create a more uniform distribution of CNT and overcome filtering effects;
- Cure, rheological, physical properties of functionalised resins were investigated and practicality of CNT manipulation was assessed;
- Manufacturing of functionalised scarf joint samples for inductive curing was proven possible.


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Consolidation-driven defect generation in severely tapered laminates

Jonathan Belnoue, Oliver Nixon-Pearson, Dmitry Ivanov, Kevin Potter and Stephen Hallett

Fibre waviness is one of the most significant defects that occurs in composites, due to the severe knockdown in mechanical properties that it causes. A key focus of this work was on thick composite parts sections, where consolidation of the ply stack leads to out of plane ply movement. This deformation can either directly lead to fibre waviness or cause excess fibre length in a ply, that in turn leads to the formation of wrinkles. Novel predictive models, built on extensive characterization of pre-pregs in small scale compaction tests, were implemented in the finite element software Abaqus as a bespoke user-defined material. The industrially relevant case study of severely tapered laminates was investigated to demonstrate the formation of defects in typical component features. The validated numerical model was used to extend the understanding gained from manufacturing trials.

Specimen manufacture

A manufacturing technique allowing good control of the pressure and tool displacements, and a homogeneous distribution of temperature through the part, was used.

Aluminium male and flat tools, attached to heater plates were bolted into a die-set that ran on linear bearings. The fixture was then placed into the bed of an Instron 600DX servo-hydraulic test machine. The pressure and temperature cycle recommended by the manufacturer was applied.

Experimental observations

A laminate with alternating 0°/90° plies at the thick and thin sections was studied. The in-plane dimension were 300 x 300 mm. Three different taper severities were studied: a baseline configuration with a 26° angle, and two extra cases with the thick section ply count increased by 5 and 10%. Resulting wrinkle severities were compared.

Model validation

The model was validated by comparing the laminate final state (thickness and wrinkle severity) with experiments.

Identification of wrinkle mechanisms

The model was used to gain better understanding of wrinkle formation mechanisms.

Sequence of events leading to the generation of wrinkles in the t2+5% demonstrator

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Development of improved fibre reinforced feedstocks for high performance 3D printing
Lourens Blok, Ben Woods, Marco Longana, HaNa Yu, Kevin Potter

Short fibre composites

To maximise strength of a discontinuous fibre composite, the fibre length $L_{\text{fibre}}$ must be above a critical fibre length $L_{\text{crit}}$ such that fibres reach their maximum strength before interfacial failure with the matrix occurs.

Additive manufacturing

Easy manufacturing of complex parts but with low mechanical properties.

A 3D printing filament reinforced with fibres above the critical fibre length, enabling low cost production of highly tailorable structures with excellent mechanical properties.

1. Short fibres above the critical fibre length are pre-aligned using the HiPerDiF [3] method.
2. A thermoplastic composite preform is made with high fibre volume fractions (>20%).
3. The thermoplastic preform is shaped into an uniform filament.
4. The reinforced filament can be used with standard printing methods.

References


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Smooth particle hydrodynamics (SPH) are used to represent the dynamics of bird matter under high-velocity impact conditions. A validated SPH bird model was obtained from previous work conducted in the UTC. Stress and delamination may be computed with the latter being modelled using a UTC mixed-mode cohesive user material subroutine.

Development of through-thickness reinforcement (TTR) architectures to achieve effective delamination management and tailored mechanical performance will be achieved through the design, manufacture and impact testing of a sub-element scale test vehicle. This test vehicle will capture delamination management effects at larger scales, and develop a method by which future TTR configurations may be designed at TRL 4-6.

We understand the need for TTR, its effects in improving and managing through-thickness performance and how it may be implemented into larger structures. However, there is a requirement to optimise the design of TTR deployment within structures to achieve maximum performance enhancement in terms of effective delamination management with minimum processing effort. Optimisation of the design process, manufacturing efficiency and mechanical performance will be achieved through the design, manufacture and impact testing of a sub-element scale test vehicle. This test vehicle will capture delamination management effects at larger scales, and develop a method by which future TTR configurations may be designed at TRL 4-6.

Parameterised design

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Specimen design

Using advanced modelling tools and techniques developed in the Bristol Composites UTC, a tapered composite subelement-level specimen is iteratively designed using a parameterised, medium-fidelity modelling approach.

2D CAD pin design

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3D pin-mapped FE mesh

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Impact modelling

Smooth particle hydrodynamics (SPH) are used to represent the dynamics of bird matter under high-velocity impact conditions. A validated SPH bird model was obtained from previous work conducted in the UTC. Stress and delamination may be computed with the latter being modelled using a UTC mixed-mode cohesive user material subroutine.

TTR design

Novel pinning patterns are generated using CAD software, and may then be auto-mapped onto pre-existing FE models via a newly-developed set of tools. Simulations can then be run with pinned laminates.

Manufacturing

Manufacturing of specimens takes place at the National Composites Centre (NCC), where specimens are laid up using carbon fibre pre-preg and pinned using a specially-developed process with complex pattern capability. They are then cured in an autoclave.

Impact testing

Gelatine impact testing of sub-element test specimens will take place at the University of Oxford’s Impact Engineering Laboratory (IEL) using the 70mm-bore gas-gun. These tests will validate simulation results and generate data on TTR performance for future design.

The described work will result in a clearly defined and validated process for efficient future TTR design at TRL 4-6, the means to further improve and tailor component mechanical performance, and provide substantial reductions in lead-time and cost of components based on optimisation of pin location, quality and manufacturing process.
Actively cooled composites via embedded vascular networks
Jim Cole, Ian Bond, Andrew Lawrie

- Use of composites at high temperatures limited by resin Glass Transition Temperature, $T_g$
- Mechanical properties severely reduced above $T_g$
- High $T_g$ resins are expensive and difficult to process
- Desire to use conventional resins above $T_g$ to achieve weight reduction
- Requires insulation (passive cooling) or heat removal (active cooling)
- Can be achieved by biologically-inspired vascular networks transporting coolant within laminate

**Background**
- Previous work has demonstrated that both water and air cooling can achieve significant temperature reductions
- Active cooling has been shown to increase short-term, high-temperature survivability under load
- Also evidence for improved property retention during long-term thermal ageing
- Technology can potentially be complemented by film cooling, depending on application

**Current research activities**
- Construction of a high temperature airflow experiment to validate existing numerical model
- Quantify thermal management potential for vascular cooling + film cooling

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McElroy, Lawrie, Bond (2015)
Dome-Shaped PLA Auxetic Cellular Honeycombs

Yousef Dobah, Sixtine Michel, Fabrizio Scarpa, Anton Shterenlikht

Abstract
Domes-shaped structures behaviour is dominated by the classical post-buckling phenomena. It’s considered dangerous in applications that protects internal parts, as aircraft’s radome and human’s protective gears. This research is aimed at minimizing the post-buckling phenomena by the use of negative Poisson’s ratio (PR) cellular geometries based on numerical simulations results.

Fabrication technique
In order to make complex dome configuration with ease and minimum cost, a 3D printing technology was used. The 3D printed materials was tested according to ASTM standards for plastics, which characterized the material as having an orthotropic behaviour.

Dome Indentation Experiments
The indentation experiments show significant change in domes load bearing behaviour affected by incorporating auxetic cellular configurations.

Finite Element Analysis (FEA)
Numerical dome buckling eigenvalue analysis shows inverse relation between PR and the load level that causes the buckling. On the other hand, FEA model is under development to predict the behaviour of such structures exposed to complex loading conditions while dealing with another layer of complexity presented by the use of 3D printed orthotropic materials.

Conclusion
-3D printed materials exhibit orthotropic performance
-FEA gives a good approximation of negative PR influence on domes buckling behaviour.
-Auxetic affect considerably domes post-buckling behaviour.
Multi-scale modelling of complex composite structures
Bassam El Said and Stephen Hallett

This Project aims to develop an integrated multi-scale modelling framework for complex composite structures. The project builds on UoB high fidelity modelling capabilities. The multi-scale framework is based on a database of meso-scale unit cell models that can contain defects and features such as wrinkles or gaps. The database models are solved under periodic boundary conditions to predict both stiffness and strength. Next, a computational homogenization module calculates the equivalent response and failure envelopes for these unit cell models. Finally, a macro-scale combined failure criteria links the meso-scale database to the macro-scale simulation.

The macro-scale failure criteria take into account the full 3D stress state (3 axial + 3 shear) and the various defects. This integrated framework has been applied to various test cases including standard tests and feature scale models. The multi-scale simulations were shown to correlate well with experimental and high fidelity model results.
Layup of composite sheet material over complex shapes is still dominated by hand layup. It relies on the dexterity, excellent vision and tactile sensing capabilities of human operators combined with their advanced problem solving skills. Replicating this in an automated environment is very challenging, and an alternative approach used in many other industries is Human-Robot collaboration. Robots can accurately and consistently apply large forces at high speeds but typically have limited dexterity and feedback capabilities. Initial trials were conducted with a human working with a 6-axis robot. The trials demonstrated that the robot collaboration approach can greatly reduce the physical efforts of the laminators, potentially increasing layup speed and reducing worker fatigue caused by prolonged physical exertion in non-ergonomic postures.

Sequential working
- The Human and robot take turns to complete separate layup tasks, avoiding potential collisions.
- Robots are typically used for high force applications such as consolidating the prepreg onto the tool.
- The Human typically arranges, shapes and manipulates the prepreg, tasks which require dexterity combined with tactile and visual feedback alongside advanced decision making.

Parallel working
- The Human and robot work simultaneously but in separate workspaces, avoiding clashes.
- Potential to dramatically cut layup time.
- Additional layers of robot-human safety will be required.

Interactive working
- The robot can act as a ‘3rd hand’, freeing the human to complete other layup tasks while working in coordination.
- The Robot will move on a predefined path to complete some aspect of layup, either consolidation of ply handling.
- The Human completes other elements that require more adjustments, feedback and dexterity.
- This will require significant additional layers of robot safety

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HiPerDuCT Programme Grant

NOTCH INSENSITIVE PSEUDO-DUCTILE QUASI-ISOTROPIC THIN-PLY CARBON/GLASS HYBRID COMPOSITES

Mohamad Fotouhi, Meisam Jalalvand, Michael Wisnom

This study introduces pseudo-ductile hybrid composites to improve notch insensitivity and to avoid free edge delamination. Un-notched, open-hole and sharp notched tests were performed on thin ply carbon/glass hybrid laminates. The results showed that the net section strength of the laminate does not change significantly due to the existence of the notch. This notch insensitivity results from subcritical damage in the laminates due to the pseudo-ductile damage mechanisms, i.e. dispersed delamination and fragmentations, which suppress the conventional damage mechanisms that govern the notched response of the laminates.

Investigated layups and their damage mode map

The quasi-isotropic hybrid laminates made from unidirectional S-glass/epoxy and T300-carbon/epoxy sub laminates. Un-notched and open-hole configurations were subjected to tension.

Conclusion:
- Notch insensitivity has been achieved in pseudo-ductile laminates.
- Subcritical damage, i.e. fibre fragmentation and dispersed delamination, suppress the conventional damage mechanisms by redistributing the stresses at the vicinity of the notch.
- A larger and more visible damage zone is observed for the hybrid laminates, compared to the conventional carbon/epoxy composites.
Laminates have been shown to exhibit considerable pseudo-ductility, via a combination of fibre rotation and gradual failure of 0° plies, with a metal-like stress-strain response. This concept has matured sufficiently to establish potential applications. Two tubular applications are explored here: a strut loaded in tension and a beam in bending.

**Concept**

- Pseudo-ductile behaviour determined by material properties, thickness of 0° and ±θ plies and the ratio between the thicknesses, \( t_\theta/t_{\theta} = B \).
- An all standard modulus layup leads to large pseudo-ductile strain, but modest initial modulus.
- Response can be tailored for a required laminate modulus, pseudo-ductile strain and strength.
- Leads to flexible design of components where gradual failure, rather than sudden and brittle, can improve performance.
- Initial pseudo-ductile concept demonstrators identified for tensile loading and bending: tubular strut and cylindrical beam.

**Tubular Strut**

- Two configurations manufactured to demonstrate:
  - Large strain capability with \([±45]_s\).
  - Pseudo-ductility with \([±26/0]_s\).
- Dimensions: 350 mm \(\times\) 50 mm
- Bolted joint designed to mimic real world connection scheme, with extensive pad up region to distribute stresses.
- Manufactured via hand layup using cylindrical mould tool.

**Results**

\([±45]_s\)

- High strains exhibited (> 7%).
- Visible 'necking' displayed by ±45 strut.
- Damage suppressed in gauge section.

\([±26/0]_s\)

- Fragmentations observed post-failure.
- Limited global non-linearity.
- Large layup defects led to premature failure.

**Cylindrical Beam**

- Motivation to develop a structural component to demonstrate pseudo-ductility in three-point bending.
- Bicycle handlebars identified as safety critical where catastrophic failures must be avoided.
- Gradual failure can improve both safety and performance.
- Control of location of failure vital to safety.

**Finite Element Analysis**

- Key drivers are requirements for EN14781 standard:
  - Maximum 15 mm displacement under a load of 1000 N.
- Layered shell approach, symmetry assumed at handlebar centre.
- Displacement applied over area to replicate stem attachment.
- Geometry sized to match common handlebar profiles.
- Layups are \([±25m/0n]_s\) where m and n increase towards beam centre to give progressively thicker laminate at highly loaded regions.

**Handbars**

- Preliminary results show \([±25m/0n]_s\) laminates sufficient initial stiffness – ongoing work to determine pseudo-ductility.

**Layups use high modulus and high strength fibres in tensile and compressive 0° plies respectively.**

1. Test results of commercially available handlebars.
2. FEA prediction well matched to tested handlebars; reaching 1340 N with applied displacement of 15 mm.
3. Surpasses EN14781 requirements (black line).
Examining the influence of graphene species on toughening mechanisms in industrially relevant epoxy resins

Ian Gent, Napatsorn Prakobboon, Liam Robinson, Cristina Vallés, Rainer Kuusvek, Robert J Young, Ian Kinloch, and Ian Hamerton

In this study, a commercial epoxy system (Cycom EPXX, ex Solvay) is modified using graphene oxide (GO) in order to modify mechanical properties. Thermal and spectral analyses are used to characterize the uncured resin blend, while blending conditions are optimized to achieve both dispersion and desirable morphology following cure. The analyses demonstrate that the incorporation of a modest quantity of GO may lead to enhancements of thermal and mechanical characteristics as evidenced by fracture toughness data.

Introduction

- Epoxy resins are widely used as resins for composite materials, but require toughening for engineering applications.
- Fracture toughness increases in these resin systems are usually achieved using thermoplastic particles.
- Increases in fracture toughness also result in reductions of stiffness and tensile properties.
- The introduction of nanomaterials have shown increases in fracture toughness and stiffness, but typically have focused on improving model resin systems rather than industrially relevant systems.

Experimental

- Proprietary components for commercial epoxy resin blend (EPXX) supplied by Solvay.
- Graphene oxide (GO - 0.5 wt%) suspended in acetone and dispersed using ultrasonication (EPXX-GO).
- Components of the blend mixed at elevated temperatures and high shear mixing.
- Complete resin blend degassed and cured at 180°C.

Results

- Morphology of the cured resin is unaffected by the addition of graphene oxide (GO).
- DSC results suggest that the incorporation of GO results in an acceleration of the curing reaction.
- DMA results show storage modulus is unaffected for EPXX-GO with the broader tan δ suggesting greater damping properties.
- Modest increase in fracture toughness with less variation amongst the samples.

Future Work

- Optimisation of EPXX-GO blending procedure to produce void free samples.
- Expanded testing schedule to include tensile, flexure, and impact testing.
- Incorporation of other graphene based nanomaterials in toughened commercial resin systems.

References


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This PhD project will investigate the influence and interaction of combinations of through-thickness (primarily compression) and shear stresses on the tensile strength of fibre reinforced composites. A bespoke test method will be developed to study the material behaviour and based on this a numerical model will be developed and validated. A successfully developed model and test method will give the opportunity to improve the design and the reliability of composite components. Such a model and test method can be applied to applications where composites are subject to complex 3D stress states and the results will give a better understanding on the strength of composites.

**State of the art**

*K.W. Gan, S.R. Hallett, M.R. Wisnom*

Bespoke test methods were developed for testing material properties in the presence of through-thickness stress. It was shown that:

- Shear strength increases with increased through-thickness compression
- Fibre direction tensile strength decreases significantly with highly increased through-thickness compressive stresses

This work did not however account for the effect of through-thickness shear on fibre tensile strength. A case that has been observed in industrial applications.

**Approaches for bespoke test method**

**Longitudinal tensile loading under combined through-thickness compressive and shear stress**

- Bi-axial test with special stamp geometry
- Bi-axial test with inserted fibre curvature in test specimen

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Efficient models for nonlinear dynamic analysis of thick composite laminates

Aewis Hii, Luiz Kawashita, Alberto Pirrera, Stephen Hallett

The scope for early stage design and optimisation of thick composite aerospace components is limited by the expensive numerical analysis of nonlinear dynamic phenomena. The common analysis methodology is the use of 8-noded solid elements with reduced integration in a nonlinear explicit dynamic finite element (FE) solver. To yield meaningful analysis, a model with large number of degrees of freedom and very small explicit time steps are often required. This is due to the complex stresses caused by the highly anisotropic layup and complex geometry. In this work, we are developing a generalised hierarchical shell formulation to address these challenges. Firstly, the condensation of 3D kinematics onto a 2D surface reduces the problem size drastically. Secondly, the hierarchical formulation can prescribe different levels of model fidelity across the analysis domain, which allow for model refinement without remeshing. The shell element is derived from Carrera’s Unified Formulation (CUF), which permits expansion of through thickness variables to be handled in a compact manner. The on-going work includes incorporation of delamination kinematics and implementation of the element in an explicit dynamic solver.

Hierarchical shell element

The hierarchical formulation allows the shell model to be asymptotically consistent with 3D elasticity.

It also allows different levels of model fidelity to be prescribed as a free parameter across the structure, to achieve higher computational efficiency.

Reducing model fidelity away from critical region.

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Numerical benchmark

Figure 1: Transverse stress distribution of a 40 mm thick composite cylinder with layup [0°,30°,90°,-45°] in bending. Benchmarked with 8-noded brick element in Abaqus.

Figure 2: Computational performance of CUF-Shell in the linear, static implicit analysis.
Novel interfaces in hybrid composite-metal struts

Jordan Jones, Luiz Kawashita, Byung Chul Kim, Stephen Hallett

This project considers a novel hybrid composite-metal joining solution for a high performance landing gear component that predominately experiences axial loads (tension and compression). The composite-metal interface is initiated by a mechanical interaction between filament wound fibre-tows and surface features (pins) sculpted onto the metal in the joint region.

Explicit Finite Element (FE) analysis is used to assess the feasibility of the proposed joining mechanism and to conduct a parametric study to ascertain optimal joint geometries which maximise structural integrity. Improvements are expected over prevalent joining techniques such as mechanical fastening; as this method achieves a direct coupling between the metallic part and the composite material’s primary load carrying constituent: the fibre reinforcement.

(a) Rendering of the structure’s components prior to filament winding: two surface-sculpted end-fittings (grey) and a cylindrical connector tube (green), which is used to provide a winding surface.

(b) FE model of the tow path on the structure according to pre-designated fibre angles and lay-up sequence. Tow is modelled as a chain of 1-dimensional beam elements with constant, circular cross section in a dry-fibre network.

(c) Tow described as a mesh of 3D continuum elements (blue) encased in resin (red). Non-coincident meshes are coupled using Lagrangian Constraints.

(d) Von Mises stress in a metallic end-fitting following joint tension. Stress concentrations are observed around base of the pins.

(e) Longitudinal stress in fibre-tow lattice. Higher stresses occur in layers with lower winding angle due to better alignment with applied load.

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Further experimental characterisation of defects and features

Mike Jones, Hafiz Ali, Luiz Kawashita and Stephen Hallett

Previous quasi-static testing has considered a range of defects and features that occur in composites manufacture under room temperature/dry conditions. Current work aims to extend the scope of testing on 2 fronts. One work stream will investigate the fatigue behaviour of specimens with defects (dry) and a second separate stream will aim to experimentally characterise quasi-static performance over a range of temperature and moisture conditions. Both investigations will provide an understanding of the basic phenomena and assist FE model development and facilitate model validation.

**Background**

Previous experimental work on defects and features included:

- Specimens with embedded out-of-plane wrinkle, gaps and/or overlaps, dropped plies, cut plies (+ pristine control specimens)
- Quasi-static tests only
  - Uni-axial tension and compression
  - Bi-axial and out-of-plane tests
- All tests performed at room temperature/dry conditions
- Some significant knockdowns in mechanical properties were observed, particularly for wrinkle defect.

**Fatigue testing (room temperature/dry)**

- Manufacture QI test specimens, 8552/IM7 material, stacking sequence as follows:
  - 8552/IM7 - [(+45, 90, -45, 0)]s
- Specimen types:
  - Pristine
  - 2 central cut plies
  - Embedded wrinkle
- Tension-tension fatigue, sinusoidal waveform, R-value = 0.1
- Range of severity levels based on mean static failure strength

**Hygro-thermal static testing**

- QI test specimens, initially pristine and with embedded wrinkle
- Specimen thickness reduced to ~4mm to reduce conditioning times
- Environmental conditioning to be carried out in Vötsch VC 7034 temperature and humidity controlled chamber at ACCIS.
- Chamber conditions 70°C and 85%RH (ref ASTM D5229)
- Quasi-static testing, initially uniaxial tension (S11), over a range of temperature/moisture conditions:
  - RT/dry
  - Cold (-18°C)
  - Hot (50° and 90°C)
  - Hot/wet

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Effect of high velocity impacts on thin composite plates

Ashwin R Kristnama, Michael Wisnom, Stephen Hallett, David Nowell*

Impacts from small and hard particles at high velocity cause foreign object damage (FOD). This work focuses on understanding the effect of FOD on damage development and component strength of thin laminates. A first level of study investigated impacts carried out over a range of velocities, and damage was observed under X-ray CT scan. The second level of study looked at the residual strength of impacted laminates from quasi-static tensile tests. FE models employing cohesive interface elements are being developed for a predictive capability.

**Experiment**

<table>
<thead>
<tr>
<th>Impact</th>
<th>Laminate configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A – edge impact</td>
<td>Material: IM7/8552</td>
</tr>
<tr>
<td>B – centre impact</td>
<td>Projectile: 3mm steel</td>
</tr>
<tr>
<td></td>
<td>cube of mass 0.22g</td>
</tr>
</tbody>
</table>

**Material:**

- Length: 250 mm
- Width: 40 mm
- Thickness: 2 mm
- [45/90/-45/0]_2S

**Tensile test – Residual Strength**

<table>
<thead>
<tr>
<th>Impact</th>
<th>Baseline (non-impacted):</th>
<th>At 350 m/s</th>
<th>Centre impact:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge</td>
<td>909 MPa</td>
<td>358 MPa</td>
<td>318 MPa</td>
</tr>
<tr>
<td>Centre</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Modelling:**

- FE models are validated against the residual tensile strength data
- UTC meshing tool to define mesh based on a unit cell
- 1mm spacing between split paths defined
- Delamination envelope and fibre fracture inserted into FE model
- Investigate effect of delamination envelope on residual tensile strength – one model with delamination envelope and one without.
- Delamination envelope decreases the residual tensile strength by 8%

**Delamination envelope inserted into FE model (multi – coloured) for an edge impact at 350 m/s.**

---

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Combined effects of load reversal and mode ratio on the fatigue behaviour of carbon/epoxy laminates

Rico Kuehlewind, Luiz Kawashita, Stephen Hallett

Fatigue loading can cause undetected crack initiation and growth. This material degradation can lead to catastrophic failure. This work focused on the recreation of complex load cases to monitor material degradation in fully reversed fatigue loading conditions. Delamination onset for small cracks with reversed Mode-II and large cracks with mixed-mode conditions has been investigated for two resin systems, IM7/8552 and M21/IMA.

Overview of results for IM7/8552:
- Fully-reversed fatigue leads to fastest crack growth of all test cases
- Fully-reversed Mode-II/Mode-II and non-reversed cases form upper and lower bounds, respectively
- Combined mixed-mode tests lie in between these two cases
- Reversed mixed-mode case must be interpreted with care, as Mode-I and Mode-II contributions change during a full load cycle

Comparison between the two material systems for fully-reversed Mode-II fatigue:
- Interlayer toughening results in much slower crack growth rate
- Interlayer toughening dissipates more energy in a delamination scenario
- Tests confirm literature data and working principle of interlayer toughening
- Further load cases to be repeated on the M21/IMA resin system

Ongoing work:
- Further characterisation of interlayer toughened resin system at different load ratios required
- Investigation of the micromechanics of fatigue crack growth in fully-reversed loading using Scanning Electron Microscopy (SEM)
- Comparison of damage mechanisms for different materials systems and correlation with observed crack growth rates
- Development of a mathematical representation of fatigue crack growth in fully-reversed fatigue loading

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Structural efficiency via stiffness adaptation

Olivia Leão, Rainer Groh, Alberto Pirrera

This work explores the concept of structural efficiency via stiffness adaptation using a T-beam model with a sinusoidal web. This geometry makes the structure inherently nonlinear due to the hidden length mechanism it develops upon loading. Initially, for small bending deformations, the beam is relatively flexible as the web acts like a corrugation, i.e. it provides little resistance to being stretched. As deformation increases, membrane stresses develop in the web causing the beam to stiffen whilst locally converting bending to stretching strain energy.

Conceptual model

Parameters
L: Length (fixed)
w: Flange width
h: Web height
t_f: Flange thickness
t_w: Web thickness
N: Number of half-waves
a: Half-wave amplitude

Boundary/load conditions and design constraints
- Simply supported beam
- Pressure load on flange
- Onset of plasticity
- Structural instability

Mechanism
Upon loading, the sinusoidal web stretches out converting bending to stretching energy.

Methodology
A parametric study was performed on FE models using a global sensitivity analysis method. This is to apportion the effect of varying each of the geometric parameters on both nonlinear response and structural efficiency of the beam.

Key findings

In the nonlinear region of the design space:
- Varying N and a individually changes our measure of nonlinearity by 50% and 20%, respectively.
- Results suggest that the parameters ratio a.N/L contributes more effectively to changes in structural efficiency (Force to failure/Mass) than the individual variation of any of the parameters.
- Wavy web profile adds little mass to structure while delaying instability, as shown through comparison of the model with highest nonlinear response (NL) against a straight design with the same T-section (figure below).

Conclusions

Greater structural efficiency is achieved for the nonlinear model compared to straight counterpart with linear response.
Development, Demonstration and Performance Validation of Composite Repair Schemes

Threat Environment
Aerospace components are exposed to a wide variety of threats during their life cycle including: service threats such as high velocity runway debris, maintenance damage from dropped tools and manufacturing events such as transportation and over machining damage.

Research
This project aims to develop repair techniques that can restore the original performance of primary aerospace structures without substantial weight or aerodynamic penalties. This will be achieved via development and testing, in a relevant environment, of two potential repair technologies. To date a review of current repair techniques has been conducted and two repair techniques to be progressed have been selected.

Impact damage in composites
Composite materials exhibit complex damage morphology that can consist of: inter and intra ply cracking, fibre breakage and fibre-matrix debonding. These can severely degrade the performance of the parent structure. Additionally, composite materials exhibit vulnerability to low velocity impacts, as they cannot deform plastically to dissipate impact energy. Barely visible impact damage (BVID) has a low detection probability but can substantially degrade the component’s performance.

Limitations of current repair technology
The bolted patch repair provides several limitations: drilling the bolt holes introduces stress raisers into the laminate which weaken the parent structure and render the bolted repair unusable for certain applications. Additionally, the repair is not aerodynamically smooth, potentially resulting in increased drag, and the repair can add substantial weight to the airframe. Currently bonded repairs are limited by the lack of repeatability, robustness and certifiability of the process.

Current repair technology
Certified repairs to primary, safety critical aerospace structures are limited to bolted plate repairs whereby a metallic or composite plate is bolted over the damaged area to provide an alternative load path. Bonded patch repairs, where the damaged material is removed in either a stepped or scarf fashion and then a patch of pristine material inserted, are certified for secondary structures but owing to their reliance on adhesion to transfer service loads are currently uncertified for primary structures.

The HiPerDiF method offers **flexibility in shaping hybrid** composites with various fibre and resin types, fibre lengths, preform patterns and fibre surface treatments.

**Hybrid Ductile Composites:**
- Aligned-discontinuous fibres
- Interlaminated
- Intraply
- Intermingled

Optimisation of **pseudo-ductile response** in discontinuous hybrid composites with fragmentation, delamination, fibres and bundles pull-out mechanism.

**Ductile response** can be achieved with **Novel architectures** of aligned short fibre composites.

**Intermingled & Intraply hybrid composites:**
High Modulus Carbon & E-Glass 3 mm Fibres Hybrid:

- Intraply
- Intermingled

Optimum hybrid configuration by modelling (Imperial College):
**Isolation of low elongation fibres**

Image: Machine Workflow
- Fibres dispersion
- Suspension flow control
- Water suction
- Fibres alignment
- Preform drying
- Pre-impregnation

**Fibre orientation head working principle:**
- A-A’ section
- Mesh belt moving direction
- Patent application (EU granted)

Optimal production process and production of different feedstock forms.
Advanced design and manufacturing concept of bend-twist coupled wind turbine blade

Vincent Maes, Terence Macquart, Paul Weaver, Alberto Pirrera

Bend-twist coupling offers improved cost efficiency for wind-turbines blades over traditional designs. Underlying models and methods remain un-validated against test data. Providing test data for model validation therefore the current aim.

Test data provides essential insight into the phenomenological nature of a problem. However, when multiple effects are involved, separating these can be tricky. Current work aims at providing a series of coupled demonstrators with increasing complexity to allow influence of different blade features to be properly characterised.

The first demonstrator, D1, is a simple monolithic box beam as shown in Fig. 1. The central flange regions have unidirectional lay-ups with fibres at 20° to the beam axis. This induces extension-shear coupling at laminate level and bend-twist coupling at beam level. The beam is designed for a tip deflection of up to 10% of its length before it loses stability or suffers material failure.

The beam is being produced from prepreg E-glass in 912 epoxy resin and laid-up by hand. The custom tool shown in Fig. 2 was designed and built to be disassembled from within to prevent damage to the part during demoulding. Lay-up, bagging, and cure are being carried out at the facilities of the National Composite Centre (NCC).

Testing will follow shortly at which point the validation of commonly used prediction methods for wind turbine blade behaviour can take place. Additional beams with representative cross-sections and internal geometries will be built and tested at a later stage of the project.

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Sponsored by: Vestas
Experimental design of a multiple delamination, mixed-mode fracture test

Yusuf Mahadik, Stephen Hallett

- Complex crack formations can occur in industrial applications - these require characterisation.
- Z-pin zones can experience multiple-cracks with varying mixed-mode ratios in sequences or simultaneously.
- Before complex experimental investigations, a validated FE testbed for a parametric study is required.
- Aim is to design a highly flexible test method that can produce multiple cracks with different mode mixity.

Potential configurations

Previous RRUTC work used a simplified FE platform to design experiments for multiple delamination characterisation within z-pin laminates. This has been extended to a multiple, mixed-mode scenario with cohesive zone - simulating both the major types of mixed-mode loading, single leg bending (SLB) and mixed-mode bending (MMB) with an extra Mode II crack inserted into the laminate.

The SLB configuration was down-selected as the platform for the study as it gives a greater flexibility in specimen configuration. The mode-mixity of the primary crack is adjusted by varying the thickness ratio. The FE model was correlated with analytical compliance and chosen for parametric study.

Parametric study

i. The crack sequence should be triggered in either order. ii. The cracks should be of different mode-mixities. iii. The mode-mixity of one crack should be tailorable to some extent.

Combination of thickness ratio and pre-crack lengths used in parametric study.

Specimen design

Parametric FE study identified potential configuration that gives separated crack sequence, different mode mixities and tailorable crack timings.

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Further experimental characterisation of TTR

Yusuf Mahadik, Hafiz Ali and Stephen Hallett

Previous research has characterised the traction-separation behaviour, including the effect of mode-mixity, multiple cracks and embedded length. The next stage is to assess their behaviour in an ‘in-service’ context. This includes considering the in-plane behaviour of laminates with z-pins considered a ‘defect’ and the degradation of behaviour after environmental aging.

Z-pins as an in-plane defect

- Z-pinning induces many features into the laminate micro structural architecture which can be considered as defects.
- The introduction of fibre waviness close to the Z-pin is the most obvious micro-structural change which occurs as the fibres are forced aside during insertion.
- Development work for manufacture of single-pin and array samples has been carried out at the NCC.

In-plane testing

Tension as well as Compression testing will be done on single and double pinned samples with varied areal densities to define the relationship between pin density and in-plane properties.

Environmental aging

Exposure to moisture and temperature degrades matrix properties in CFRP laminates.

Introduction of micro-fasteners (z-pins) can significantly increase moisture ingress.

The effect of mixed-mode delamination with environmental aging is the next step to generating a more comprehensive TTR fracture model.

Z-pins were shown to increase the moisture absorption rate.

Caused by interfacial cracks, voids within the pins and the higher diffusivity along the fibre direction of the pin.

Conditioning to be performed in temperature and humidity controlled chamber at ACCIS.

Conditions from ASTM 5229, 84% Humidity, 75°C

Literature indicates a 4.5mm z-pin laminate reaches 1.25% weight gain in 100 days.

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Large mesh techniques for cohesive zone modelling
Supratik Mukhopadhyay and Stephen Hallett

Delamination in composites is simulated using layers of cohesive elements between solid ply elements. However, a fine mesh is usually required to capture the nonlinear traction distribution in the process zone ahead of the crack front. This makes it computationally expensive for industrial scale applications. The present work relaxes this constraint by artificially reducing the initiation stress of the bilinear cohesive law, in a controlled region around the evolving crack front with the aid of a neighbour tracking algorithm, thereby artificially extending the process zone and allowing a coarse mesh to be used.

In-situ strength reduction scheme
• Element size of the mesh is recorded automatically.
• A suitable reduced strength is calculated based on the element size.
• As soon as the first integration point of an element is damaged, the algorithm is activated.
• The nominal strength is reduced in a controlled region around the damaged element.
• The crack front is tracked dynamically using a neighbor search algorithm and the strength reduction zone is updated as the crack evolves.

Strength reduction in the bilinear law governed by the element size requirement

End-notched-flexure (ENF) specimen showing stable delamination growth within 4mm mesh using in-situ strength reduction

Oblique SPH impact on a clamped plate

Damaged area in a fine mesh (left) and coarse mesh (right)
Multi-scale characterization and modelling of tufted composite structures

Camilla Osmiani, Galal Mohamed, Ivana K. Partridge

Tufting belongs to the class of through-the-thickness Reinforcement techniques developed to improve the delamination resistance of 2D composites. It is a single sided stitching technique in which a thread is inserted into a dry preform to make it locally 3-dimensional. The aim of the current project is to understand how tufts counteract the propagation of delamination in quasi-static mixed mode conditions. A multi-scale approach has been adopted for this purpose. Mechanical tests on miniature single-tuft coupons and fracture tests on tufted DCB, ENF and MMB coupons (1% areal density) have been carried out. Finite element models of the tested coupons have been developed to identify which parameters, both geometrical and physical, have the largest influence on the performance of tufts.

Level 1: Single-Tuft Tests and Modelling

X-ray CT, SEM and optical microscopy images from tested and pristine single-tuft coupons: carbon fibre tuft into a 0/90 carbon NCF/epoxy composite. The coupons were tested in tension (\(\phi = 0\)), pure shear (\(\phi = 1\)) and mixed shear/tension (\(\phi = 0.25\)). One of the coupons was modelled in a FE environment to study the effect of geometry, debonding and matrix deformation on the mechanical response of tufts.

Level 2: Arrays of Tufts, Testing and Modelling

Interface elements and axial connectors have been adopted to model tufts at the meso-scale. The bridging law of the tuft has been assigned as constitutive law to those elements or connectors. The level of detail required to the bridging law has been investigated by implementing various shapes of cohesive laws.
PERIODIC INCLUSIONS IN AUXETIC MEDIA
Rita Palumbo, Fabrizio Scarpa, Mohamed Ichchou, Dmitry Ivanov, Olivier Bareille

Within Marie Skłodowska-Curie actions VIPER project, this PhD Position is based at University of Bristol and Ecole Centrale de Lyon (FR), in collaboration with University of Sherbrooke (Canada) and the engineering company iChrome (Bristol, UK). The research is mainly focused on the enhancement of sandwich panels vibroacoustic properties by means of state-of-the-art materials and technologies. The topic will be treated from the manufacturing, numerical/analytic and experimental testing standpoints.

Research objectives

Within this research project, a honeycomb core with square cells has been adopted (manufacturing: strips slotting method, figure on the right).
In sandwich panels, the high stiffness-to-weight ratio usually leads to bad vibroacoustic performances, and the higher the ratio the worse they are. Therefore, with the aim of achieving enhanced vibroacoustic characteristics, different aspects will be considered:

1. Increase in the vibration damping, which mainly affects the behaviour in the low frequencies range;
2. Increase in the shear transition frequency to have a higher Transmission Loss through the panel at medium-high frequencies;
3. Increase in the acoustic absorption coefficient.

Methods

In order to achieve the three main objectives reported above, different manufacturing/material solutions are being considered and numerically studied.

Two possible configurations of inserts. They consist of Carbon-Nanotubes-reinforced resin and can be easily manufactured by means of a modified 3D printing system recently developed at the University of Bristol under a UK EPSRC grant. The expected benefits from using this kind of inserts are increased vibration damping and core’s strength. PMMA-decorated nanotubes are also being considered as a possible option, in order to increase the modulus of the core as well.

Results

Vibration transmissibility tests were carried out on natural-fiber hexagonal-cell honeycomb cores of different heights, manufactured by means of Kirigami-inspired techniques.

Kirigami-inspired manufacturing procedure of natural-fiber hexagonal-cell honeycombs. Epoxy resin was used to glue the adjacent walls together.

Set-up and results of vibration transmissibility tests carried out on honeycomb samples of different heights (curves in function of the height, [mm]).
Static and buckling analysis of composite structures through advanced high-fidelity models

Mayank Patni, Sergio Minera, Paul M. Weaver, Alberto Pirrera

Calculating accurate 3D stress fields for structural tailoring is often a complex, computationally expensive task. This is especially so for lightweight, thin-walled composite parts with stiffening elements such as stringers and ribs, and localised features such as stringer terminations and rib foot connectors. The so-called Unified Formulation offers a computationally efficient means of capturing high-fidelity 3D stress fields and considerable scope to analyse such features in a robust and direct way.

Objective

On the basis of the Unified Formulation, new, accurate and computationally cheap design and optimization methods are being developed, with particular attention paid to aerospace structures and the buckling analysis of thin-walled shells.

Task 1: Development of enhanced models for accurate 3D stress fields around complex geometries.

Task 2: Development of advanced models for buckling of thin-walled structure

Task 3: Shell model based in 2D Unified Formulation

Supported by H2020 MSCA ITN – ETN
Development of high performance composites by optimising the matrix

Thomas Pozegic, Ian Hamerton and Michael Wisnom

Exploration of alternative high performance polymer matrices to develop ductile composites by enhancing shear properties

Background

Compressive properties are limited by shear instability and will be studied by modifying the polymer matrix - high performance polymers with high strength and modulus.

Polymers

Polybenzimidazole (PBI)

Highest tensile and compressive strength of any unfilled polymer ($T_g = 427 \, ^\circ C$)

Solvent

1-ethyl-3-methylimidazolium acetate [EMIM]OAc

‘Green’ alternative to toxic solvents

Methodology

1. Thermal Characterisation of PBI

2. Prepare Polymer Films

3. Tensile Mechanical Results Demonstrate Consolidation

4. Future Work

Thermal Characterisation of PBI

Presence of moisture & phenol

Polymers

Polymers

Compressive properties

Minimise loss in strength and modulus

Future Work

Compression

Tensile

Modified Matrix

Modified Matrix

$[0]_n$ to $[45]_n$
Local grading of composite architectures

Arjun Radhakrishnan+, Ian Hamerton+, Milo Shaffer*, Farbizio Scarpa+, Dmitry S Ivanov+

+University of Bristol, *Imperial College London

This research demonstrates feasibility of using local grading of composite structures to improve structural performance and functionality of composites. Combination of Liquid Resin Printing (LRP) and consolidation programmes allows to achieve controlled morphology of the graded patch.

A localised manipulation of material properties allows to increase the loading of additives, decrease the cost of manufacturing properties compared to bulk modification of composites, create greater stiffness contrast, improve structural performance, and open a larger material design space for optimisation.

Step 1: Liquid resin printing of enhanced matrix
Step 2: Thermal management and consolidation of patch
Step 3: Resin infusion of graded structure

Processing multi-matrix composites

Morphology of graded composites
- Distribution of additives is controlled through injection parameters, filtration mechanisms (natural grading) and consolidation programmes (controlled grading).
- Through thickness-electrical conductivity mapping shows that various patch morphologies and additive distributions may be achieved.

Mechanical properties of graded composites
- Local enhancement of the properties (e.g. around the stress concentrator) is shown to improve mechanical performance of the material.
- Various grading materials are considered
- Increase of 17% and 24% of strain-to-failure and strength respectively is observed in open hole tensile tests by grading of glass-epoxy braided samples.

Consolidation programmes are tailored to cure kinetics and rheology of injected resin.
New approach is developed for consolidating the graded patches.
Varying consolidation parameters is shown to result in different patch morphology.

Examples of patches consolidated using different programmes

Grading of composites is shown to affect stress distribution in composite through a number of mechanisms:
- Load flow due to stiffness to the presence of internal interfaces
- Damage mechanisms due to combination of different matrices.

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Design & manufacture of a composite FishBAC camber morphing device

Andrés Rivero, Paul Weaver, Jonathan Cooper and Benjamin Woods

The Fishbone Active Camber (FishBAC) concept is a morphing trailing edge device capable of generating large, smooth and continuous changes in aerofoil camber distribution from a biologically inspired compliant structure. It has already shown promising results in terms of its large lift control authority, with significantly lower drag penalty than traditional trailing edge flaps. This work presents progress on the design, analysis and manufacture of the first FishBAC wind tunnel model made with fibre-reinforced composite laminates. The wind tunnel model was designed using a previously developed novel analytical tool that models highly discontinuous composite plate structures using Rayleigh-Ritz Method and Classical Laminate Theory.

Fishbone Active Camber Device

Benefits

- Smooth and continuous change in camber
- Lower noise and profile drag
- Higher $\frac{C_L}{D_{max}}$

Analytical Modelling

- Kirchhoff-Love Plate Theory
- Classical Laminate Theory
- Rayleigh-Ritz Method
- Chebyshev Polynomials of the First Kind
- Courant’s Penalty Method for discontinuities
- Artificial Torsional Springs

Analysis

- Analytical
- Finite Element Method

Manufacture

- Carbon Fibre Spine (FishBAC)
- Leading Edge Mounting Plate
- Box Spar
- Removable Trailing Edge Clamp
- Carbon Fibre Spine (FishBAC)
- Carbon Fibre Rods

Presented at 10th Annual ACCIS Conference
Bristol Composites Institute, University of Bristol
Bristol, UK, 15th November 2017

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Novel matrix for GFRP wind turbine blades

Bethany Russell, Carwyn Ward, Shinji Takeda, Ian Hamerton

The project aims to conduct preliminary studies into an anhydride-cured epoxy resin system, which has been developed by Hitachi Chemical Company Ltd (HCCL). The thermo-mechanical properties of the resin and the processing parameters for vacuum infusion were characterised. HCCL claimed this GFRP system had shown improved interlaminar properties compared to their current system, hence this was verified using short beam shear and impact testing.

Resin formulation

bisphenol A diglycidyl ether (DEGBA)
tetrahydromethylphthalic anhydride (MTHPA)
ancamine K54 (tertiary amine)

Interlaminar properties

- Interlaminar shear strength evaluated to be 67 MPa. Previously used amine-cured epoxy system had ILSS of 56 MPa.
- Impact resistance is a further indicator of interlaminar properties. Test setup for qualitative assessment of specimens shown in Figure 1.
- Assessment of interfacial shear strength to be characterised using microbond testing is currently ongoing.

Cure cycle optimisation

- Can the cure cycle at 75 °C be halved from 12 hours to 6 hours?
- Isothermal DSC (Figure 2) shows that after 6 hours the resin has reached its maximum degree of cure (86%).
- Need to assess reaction kinetics and mechanical performance further.

Figure 1: i) Impact testing setup ii) CVID from central impact (front and back face).

Figure 2: Plot showing degree of cure vs time.

Future work

To understand the reason for the improvement in interlaminar properties seen when using an anhydride-cured epoxy resin system, and to assess the effect of varying the anhydride chemical structure on resin properties. Future work will also encompass assessing methods to optimise the cure looking at manufacturing issues which are encountered in the manufacture of composite wind turbine blades.

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Numerical modelling of TTR as in-plane defect

Xiaochuan (Ric) Sun and Stephen Hallett

Through-Thickness Reinforcement (TTR), known as ‘z-pins’, increase the in-plane shear strength, interlaminar fracture toughness and impact damage resistance for laminated composites. However, all available pinning techniques unavoidably disrupt in-plane fibre alignment and create eyelet shape resin-rich pockets, which may cause degradation of the in-plane properties of the composites. This project is to develop concept of determining the effects of z-pins on the in-plane tensile and compressive strength of laminated composite using high-fidelity numerical modelling.

Modelling Strategy

Modelling Approaches

• Using high-fidelity full size single pin model to identify possible failure modes and understand the failure mechanisms

• Using unit cell model under periodic boundary conditions to model multiple delaminations to account for different pin densities

Initial Results

• Single pin under uniaxial tension of the full size model

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Variable stiffness composite laminates for doubly curved plates using lamination parameters

Matthew Thomas, Paul Weaver and Stephen Hallett

A methodology is presented for the optimisation of variable stiffness composite laminates for complex doubly curved geometries. As an example, this is here applied to a pre-twisted plate subjected to combined centrifugal and pressure loading. Lamination parameters are varied over the geometry using spline surface interpolation over a grid of control points and the optimal values found using a gradient based optimiser. A MATLAB script was developed to define variable angle tow paths over a doubly curved geometry. The tow paths for every ply were found using a two-stage optimisation routine. The variable angle tow laminate designed showed good agreement to the optimal stiffness found through optimisation of the lamination parameter distribution.

• Lamination parameters (LP) reduce number of variables to define laminate stiffness.
• LP design space is convex and continuous, allowing for fast and efficient optimisation.
• LP were varied over a pre-twisted plate using spline surface interpolation (fig 2) of control point values (fig 1).
• The sum of nodal displacements was minimized via gradient-based optimisation using control point LP values.
• A MATLAB script created to define variable angle tow (VAT) paths onto doubly curved surfaces, using tow vectors to calculate local fibre angle.

Minimise

\[ f(\xi) = \sum_{j=1}^{m} \left( \sum_{i=1}^{12} (\xi_i - \xi_{opt})^2 \right) \]

where \( i \) is the LP index, \( j \) is the element number and \( m \) is the total number of elements.
Simulations of graphene nanoribbons for use in polymer composites

Mat Tolladay, Dmitry Ivanov, Neil Allan and Fabrizio Scarpa

Many of the limitations of conventional fibre reinforced polymer (FRP) composites are due to the mechanical properties of polymers. Improving their mechanical properties is not trivial. FRPs are themselves a method for improving polymer performance. One potential route for improving polymers further is to reinforce them at the nanoscale using lightweight, low density reinforcements such as carbon nanotubes, graphene platelets or graphene nanoribbons. Another newly developed potential reinforcement is chevron type graphene nanoribbons (CTGNRs) which have a large edge to length ratio which results in many edge carbon atoms that can be modified by the addition of functional groups. This work seeks to investigate where and how additional molecules will adsorb onto CTGNRs, what density of adsorbed groups can be achieved and what effect this has on the mechanical properties of the ribbons and a CTGNR reinforced polymer.

A chevron type graphene nanoribbon is made of lengthwise repeats of V-shaped nanoribbon. When a lengthwise load is applied the ribbon stretches with atoms at the apex of each chevron buckling out of plane.

The out of plane buckling produces a nonlinear stress-strain response in the material. CTGNRs still possess a high strain to failure and high strength.

The carbons at the edges of the ribbon are more reactive than the carbons in the bulk. This shows the edge sites offer many possible sites for functionalisation along the length of the ribbon.

The edge sites can be used to bond to adatoms or functional groups but it is unknown if the CTGNRs will saturate before all the edge sites are used. It is also unknown if any patterns occur in the adsorption sites.

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Testing and modelling of porosity defects

Iryna Tretiak, Luiz Kawashita, Stephen Hallett

The presence of porosity defects in composite materials is commonly observed, and it has been shown to have a detrimental effect on the matrix-dominated mechanical properties. Different material systems, stacking sequences and processing parameters can affect the distribution and morphology of voids. It is crucial to understand the processes of void formation, which determine their sizes, shapes and distribution.

**Main objective of this project:** to understand the formation of voids in composite laminates and their effect on mechanical performance, using a combination of FE analysis, advanced testing and characterisation methods.

A bespoke manufacturing method has been developed that creates laminates with controlled levels of porosity, by carefully controlling temperature (T) and pressure (P).

### Results

**IM7/8552**

<table>
<thead>
<tr>
<th>P, MPa</th>
<th>T, °C</th>
<th>Batch 1</th>
<th>Batch 2</th>
<th>Batch 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>120</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

curing @ 180°C for 5 hours

**IMA/M21**

<table>
<thead>
<tr>
<th>P, MPa</th>
<th>T, °C</th>
<th>Batch 1</th>
<th>Batch 2</th>
<th>Batch 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>120</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

curing @ 180°C for 3 hrs + vacuum pressure

- For IM7/8552: Voids with higher volume are more elongated.
- For IM7/8552: Many small spherical voids have the same effect on ILSS as a few large elongated ones.
- For IMA/M21: many small spherical voids have the same effect on ILSS as a few large spherical ones.

### Conclusions and future work

1. Proposed temperature and pressure-controlled manufacturing process allowed samples with a consistent level of porosity to be made
2. Compaction temperature had a strong effect on the void content of IM7/8552 panels but not for IMA/M21
3. Morphology of the interply voids was found to be different for the material systems: needle-like in IM7/8552 and circular in IMA/M21
4. Statistical analysis was performed to assess the effect of the void morphology on the ILSS
5. Smaller spherical voids with constant volume, centred in highly stressed regions, have the same effect as fewer, larger and elongated voids

Void volume and sphericity distribution in IM7/8552
Hybrid reinforced thermoplastic composites

Mario A. Valverde, Stephen Hallett, Luiz Kawashita, Maik Gude, Robert Kupfer

Thermoplastic composite overmoulding is an integrated process to manufacture multifunctional hybrid components with low cycle times. During part fabrication, a thermoplastic matrix laminate (organosheet) is thermoformed during clamping whilst a short fibre-reinforced polymer is injected to form the overmoulded structure - capable of serving as stiffening features or functional parts. This research is aimed at understanding the influence of process parameters and component design on the consolidation characteristics of the continuous fibre base and overinjected architecture as well as the properties of the short fibre/continuous fibre interface. With a fundamental understanding of the material thermomechanical behaviour, suitable and design guidelines and processing windows can be established to yield repeatable high-performance overmoulded components.

Component Design & Manufacture

- CF/PA6 overmoulded ribbed plates to be manufactured (four different rib designs, see Fig. 1) with varying injection temperatures to assess the influence of processing conditions on final part quality.
- CF/PEEK overmoulded bracket to be designed and manufactured using ILK production capabilities and modelling tools developed at Bristol UTC.

Material Characterisation

- Thermal profile of rib 2 (Fig. 2b) shows higher flow front temperature than rib 1, suggesting higher organosheet bonding due to the increased interfacial temperature.
- Cross sectional micrographs are to be taken along the rib length to capture the fibre orientation and content.
- Comparisons to be made with the predicted fibre analysis from MoldFlow simulations to understand of the influence of the rib geometry

Structural Evaluation

- Tensile tests on T-specimens cut from CF/PPS ribbed plates showed increasing max. bond strength with decreasing interface width (Fig. 3.)
- High-speed footage reveals that insufficient clamping during loading leads to premature organosheet damage and crack initiation (Fig. 4.)

Figure 1: Organosheet base (woven fabric) with four overmoulded ribs (short fibre-reinforced polymer.)

Figure 2: Rib thermal profiles over time (a) and flow front temperature along the rib length, from MoldFlow simulations of CF/PEEK ribbed plates

Figure 3: Tensile strengths of interfaces for various rib designs

Figure 4: Progressive failure of T-specimen under tensile load
Fatigue behaviour of CFRP composites under environmental conditions

Georgios Voudouris, Dario Di Maio, Ibrahim Sever

The main objective of this project is to generate understanding regarding the High Cycle Fatigue behaviour of CFRP under different Environmental Conditions, integrating a Dynamic Testing Method and a FE Model.

Internal temperature evolution of a specimen during vibration fatigue testing can be separated into 3 stages. Endurance tests are run until critical event occurs. Critical Event = Sudden change in phase of the system.

- It can be challenging to study a material’s behaviour through its thickness.
- A multi-physics model was created to give insight to this behaviour.
- Which can find application on real life composite components.

For **Self-Heating** (Equilibrium Stage A) — due to Micro-Damage Stage B):
- **Modal Analysis** → **Heat Transfer Analysis**

![Temperature Distribution](image1)

- For **Critical Event** (Stage C):
  - **Modal Analysis** → **Static Analysis (Friction Simulation)** → **Heat Transfer Analysis**

![Temperature Distribution](image2)

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New experiments for in-plane shear characterisation of uncured prepreg

Yi Wang, Dmitry Ivanov, Jonathan Belnoue, James Kratz, BC Eric Kim, Stephen Hallett

Automated Fibre Placement (AFP) is becoming one of the mainstream composites manufacturing techniques in commercial aerospace. However, one of the limitations is the occurrence of the defects generated in the tow steering process, e.g. wrinkles and tow pull off. Defect formation is closely related to the in- and out of plane properties of uncured prepreg. This work focuses on the in-plane shear behaviour characterization of thermoset prepreg by a unidirectional off-axis tensile test, taking into account the layup speed and tow width, to better understand and further simulate the AFP process.

Table 1 Test Matrix

<table>
<thead>
<tr>
<th>Different thickness</th>
<th>3 Layers</th>
<th>4 Layers</th>
<th>5 Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain rates (0.001,0.01,0.05 s⁻¹)</td>
<td>3 rates × 5 repeats</td>
<td>3 rates × 5 repeats</td>
<td>3 rates × 5 repeats</td>
</tr>
<tr>
<td>Tow width (6 mm/8 mm)</td>
<td>2 widths × 5 repeats</td>
<td>2 widths × 5 repeats</td>
<td>2 widths × 5 repeats</td>
</tr>
</tbody>
</table>

Conclusions:
- This test allows extraction of the non-linear in-plane shear stress/strain relationship of uncured prepreg;
- The shear behaviour of uncured prepreg does not vary much with different thickness specimens;
- The stiffness of the material is heavily dependent on the test rates.

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Vertically aligned carbon nanotubes (VACNTs) are investigated as a interlayer reinforcement technique. This alternative to Z-pinning and interlayer particle ‘toughening’ offers negligible interference to the laminate architecture, thereby minimising in-plane elastic property losses and mass gains. Discrete strengthening aims to increase laminate fracture toughness and control initial delamination location.

VACNTs placed within the interlaminar region

Available as pre-impregnated films

~20μm thick interface

Vertically aligned carbon nanotubes (VACNTs)

Material Characterisation – Fracture Toughness

Specimens Tested: (i) Unreinforced, (ii) Resin Reinforced and (iii) VACNT Reinforced

Mode I (Opening) – DCB

VACNTs offer ~15-20% increase in $G_{IC}$ compared to an unreinforced laminate.

Crack propagation less stable through VACNTs, likely due to variable nanotube engagement with fibres.

Mode II (Shearing) – ELS

VACNTs offer ~10-15% increase in $G_{IIC}$ compared to an unreinforced laminate.

VACNTs offer similar $G_{IIC}$ enhancement with respect to a resin reinforced interleaved laminate.

Fracture toughness likely to be improved further with shorter nanotube length, so as to minimise nanotube curling and hence promote greater fibre engagement. This will be the project’s premise for future work.

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Fatigue behaviour of pseudo-ductile thin ply angle-ply carbon fibre laminates

Xun Wu, Jonathan Fuller, Michael Wisnom

Pseudo-ductile tensile stress-strain responses have been achieved by using a thin ply angle-ply approach, with laminates in the form of $[\pm \theta / 0]_s$. Periodic fibre fragmentation in the central $0^\circ$ plies and dispersed local delaminations introduce pseudo-ductile strains. The objective of this work is to experimentally study these pseudo-ductile laminates subjected to tension-tension fatigue loading, in order to investigate the stiffness changes and understand damage progression within them during cyclic loading.

Experimental programme:
- Laminates with two different layups MR60-M55 [27/0]s and TC35-TC35 [±26/0]s were tested in tensile fatigue at a frequency of 2Hz and R ratio of 0.1.
- Two sets of tests were performed:
  - fatigue without pre-fracture: pristine specimens tested within elastic region
  - fatigue with pre-fracture: pre-load specimens to a strain higher than the "yield" strain, then tested in tensile fatigue

MR60-M55 [±27/0]s:
- Fatigue without pre-fracture: No modulus loss during cycling at 80% of $\sigma_{\text{yield}}$, and no obvious damage was observed via CT-scan.

TC35-TC35 [±26/0]s:
- Fatigue without pre-fracture: No modulus loss during cycling at 80% of $\sigma_{\text{yield}}$, and no obvious damage was observed via CT-scan.

Fatigue with pre-fracture:
- Specimens were pre-loaded to a strain of 0.73%, 0.03% higher than the "yield" strain.
- Significant stiffness reduction was observed, with a constant degradation rate.
- Delamination dominated failure mode observed at $0/-T$ interface.

Fatigue with pre-fracture:
- Specimens were pre-loaded to a strain of 2.1%, 0.2% higher than the "yield" strain.
- Specimens completely failed at less than 3,000 cycles.
- Delamination dominated failure mode observed at $+q/-q$ interface, initiating from the pre-fractured fibre in the $0^\circ$ plies.
Meta-compliance and energy dissipation in cactus-based solids

Ioannis Zampetakis, Alistair Hetherington¹, Adam Perriman², Fabrizio Scarpa

1. School of Biological Sciences, University of Bristol, BS8 1QT Bristol, United Kingdom, 2. School of Cellular and Molecular Medicine, University of Bristol, BS8 1TD Bristol, United Kingdom

The research programme is centred on the development of novel natural fibre based composites for energy dissipation applications, with a strong focus on impact absorption. Significantly, cactus fibres from Opuntia Ficus Indica have shown a 7 fold increase in flexural stiffness and a 4.2 fold increase in energy dissipation per volume when implemented as a matrix reinforcement¹. A multiscale characterization protocol provided an insight into the structural originality of the fibres. This enabled the generation of a 3D rendered model for the production of 3D Printed PLA analogues for the evaluation of their potential as bioinspired structural reinforcement constituents. The structural analysis revealed that the fractal nature of the cactus fibres was maintained when processed into a powder format. Moreover, we have encouraging preliminary results of cactus powder reinforced polypropylene composites. This in turn prompted the pursuit of a multiscale reinforcement methodology using different formats of the fibres as a structural reinforcement for different matrices for defence applications.

• Multiscale fractal geometry analytical methodology developed.

• Fractal Order of 1.8 maintained across scales and formats.

Conclusions and Future Work

• Multiscale morphological analysis reveals a fractal nature maintained across scales and formats.
• Cactus fibre architecture can be modelled and replicated demonstrating significant specific flexural stress.
• Inherent fractality enables the reinforcement of matrices through cactus in powder format.
• Cactus fibres will serve as a unique energy dissipation approach.

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Advanced modelling techniques of fatigue delamination in composites

Bing Zhang, Luiz Kawashita, Stephen Hallett

Interlaminar failure (delamination) is recognised as a main cause of catastrophic failure in composite laminates. Cyclically loading on composite laminates can induce interlaminar failure at lower load levels than under static conditions. Thus, modern engineers usually have to take into account the fatigue life when designing a composite structure. This project aims to build up advanced finite-element modelling techniques that can be employed by engineers to evaluate the delamination resistance of a composite structure when it experiences fatigue loading.

Specifically, three modelling strategies will be investigated based on the commercial FE package Abaqus/Explicit

- VUCD approach (a vumat user-defined material subroutine and single-integration C3D8R elements)
- VUCH approach (a vumat material subroutine and four-integration COH3D8 elements)
- VU² approach (a vumat subroutine + a vuel user-defined element subroutine), respectively.

The Bristol fatigue delamination predicting formulation based on the bi-linear cohesive law that has been recently improved is complied into these three packages.

Virtual fatigue loading and fatigue cohesive law

VUCD approach
It combines a user-defined material subroutine (vumat) and single-integration C3D8R elements.

VUCH approach
It combines a user-defined material subroutine (vumat) and four-integration COH3D8 elements.

VU² approach
It comprises a user-defined material subroutine (vumat) and a user-defined element subroutine (vuel).

Nomenclature I

- $G$: Energy release rate
- $a$: Crack length
- $N$: Number of cycles
- $c$: Paris law constant
- $m$: Paris law exponent

Nomenclature II

- $P_{max}$: Fatigue severity
- $f_N$: Pseudo frequency
- $\delta$: Interface relative displacement
- $\sigma$: Interface traction

da/dN = c * $G_{max}^m$

Algorithm for single-integration elements.

Build fatigue severity

Simulation of fatigue loading.

Fatigue loading.

Static/fatigue cohesive law.

$G_{max} = max(G_{Elem1}, G_{Elem2})$

da/dN = c * $G_{max}^m$

Algorithm for multi-integration elements.

G_{Avg} = (G_{IP1} + G_{IP2} + G_{IP3} + G_{IP4})/4

G_{max} = max(G_{Avg1}, G_{Avg2})

da/dN = c * $G_{max}^m$

Elem. 1 (failed) (crack-tip)

Elem. 2 (crack-tip)

Elem. 1 (failed) (crack-tip)

Elem. 2 (crack-tip)

Elem. 1 (failed) (crack-tip)

Elem. 2 (crack-tip)
Manufacturing of nature inspired composite aircraft designs: CTS (Continuous Tow Shearing)

Evangelos Zympeloudis, Paul Weaver, Kevin Potter, Byung Chul Kim

- Composites are only strong in the fibre direction
- Stacking of straight fibre layers provides strength in all directions
- But results in surplus reinforcement in areas where it is not needed

Fibre Steering

Curved fibres lead to variable stiffness structures:
- Structural optimisation for aircraft components of reduced weight
- Aeroelastic tailoring for wings that adapt to different flight conditions

Defects

- Gaps
- Overlaps
- Fibre Buckling

Manufacturing of Curved Fibre Composites

- In-plane bending
- In-plane shearing

Dry Fabric Layup
- Flexibility in material format
- Low cost process

Prepreg Layup
- Narrow processing window
- High quality fibre steering

Continuous Tow Shearing (CTS)

- UD Fabric / Prepreg
- Resin tape (used only with UD Fabric)
- Shearing Mechanism
- Paper take-up rollers
Bristol-Dresden University Technology Partnership (UTP)

Established in 2012 with the objective: ‘To work with Dresden as a focus for composites research activities, liaising with other universities to provide a coordinated programme to meet the needs of Rolls-Royce’

Joint project case studies

Dresden to Bristol student intern (2016) – Philipp Götze

‘Design, manufacture and commissioning of an in-situ mechanical testing capability for the X-ray CT scanners at Bristol’

- Carry out analysis of crack initiation, crack growth, strain mapping, adhesive bond evaluation.
- Create a working prototype made mainly from 3D printed or easily procurable parts.


‘Modelling the degradation of Z-pins under cyclic loading conditions’

- Characterisation and modelling of Z-pins and Z-pinned laminates under cycling loading.
- Development of new fatigue test protocols for Z-pinned laminates.

Bristol-Dresden Joint PhD (2016-present) – Mario Valverde

‘Hybrid reinforced thermoplastic composites’

- Combining the ease of manufacture of short-fibre injection moulding with the performance advantages of continuous carbon fibres.
- Developing a fundamental understanding of the manufacturing processes and how these affect design.
- Investigate failure mechanisms, defects and performance prediction.

Bristol to Dresden student intern (2016) – Ambreen Hussain

- Developing a method to manufacture DCB (double cantilever beam) specimens for the AF163_2U structural adhesive.
- Design of a tool to laterally align the DCB specimens during manufacture, ensuring the validity of the tests.