Next Generation Fibre-Reinforced Composites: a Full Scale Redesign for Compression

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Next generation fibre-reinforced composites (NextCOMP) Slide-pack

Public distribution, January 2023

https://nextcomp.ac.uk

Next COMP
Next Generation
Fibre-Reinforced Composites

Imperial College London

The Composites Centre
for research, modelling, testing and training in advanced composites

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Bristol Composites Institute

UK Research and Innovation

Engineering and Physical Sciences Research Council

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[dstl]
The Science Inside

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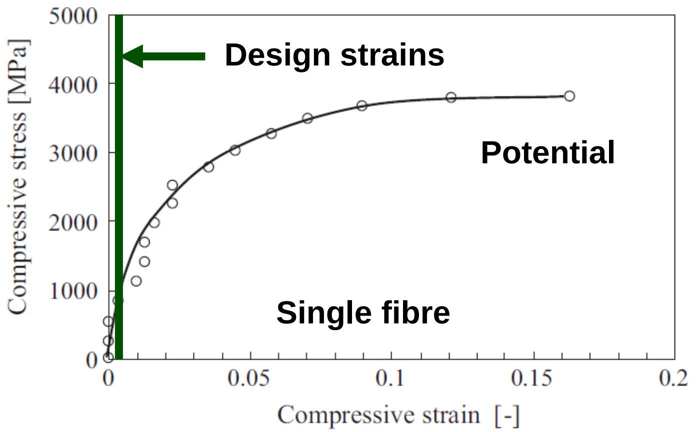
NEXTCOMP

A new generation of hierarchical composite materials, designed from first principles, to deliver a substantial improvement in practical compression performance.

- To realise the full potential of the fibres, exploiting the latest developments in materials, processing, characterisation, and modelling.
- To exemplify the value of design and integration of mechanisms across multiple length-scales by addressing urgent performance requirements in compression and post-impact strength.
- To create and characterise new hierarchical composite systems directed at the long-standing challenge of improving compression performance and damage tolerance, simultaneously.
- To extend the strain allowable boundary through a full-scale redesign for compression, creating safer and more efficient composite architectures.
- To establish the next generation of composites leaders and an integrated collaborative network.



Source: M Ueda et al., Longitudinal direct compression test of a single carbon fiber in a scanning electron microscope, *Composites: Part A*, Vol. 67, 2014, pages 96-101.

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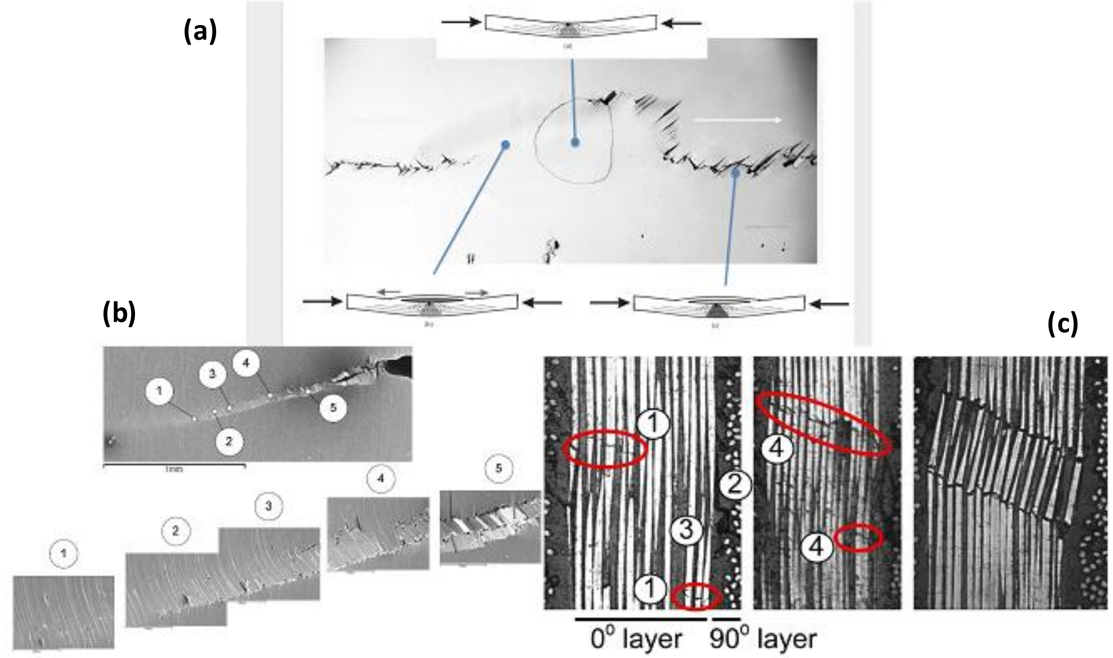
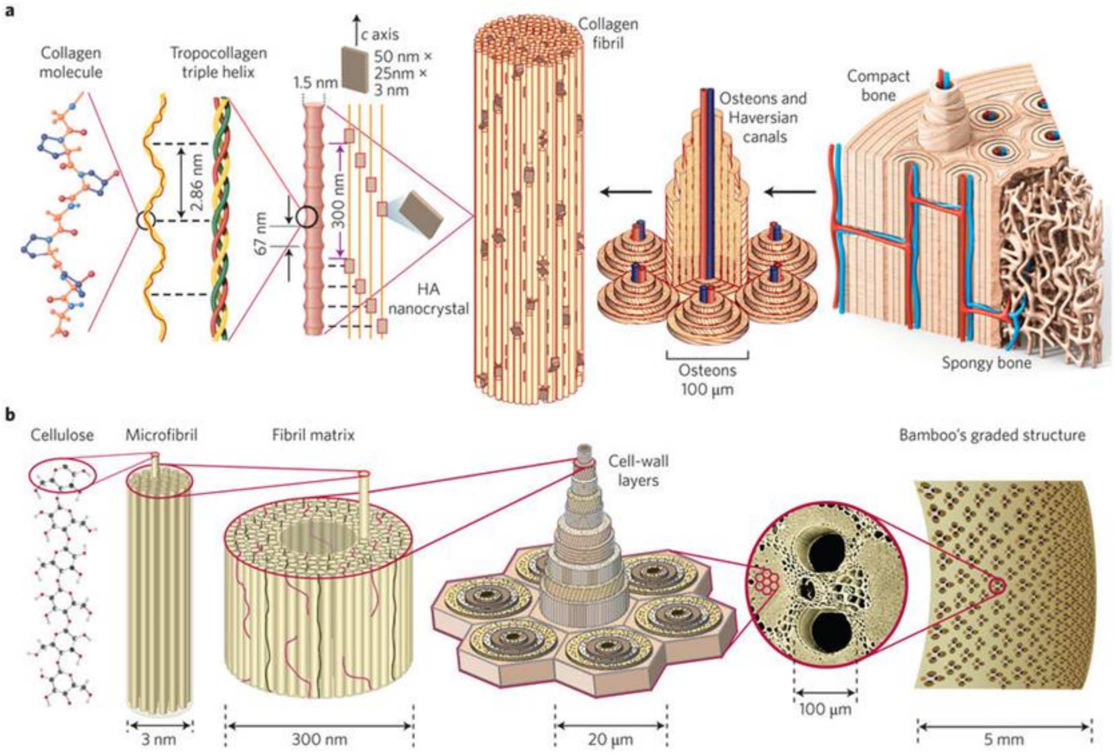
HIERARCHY

Hierarchical problem



Modified from sources including; ST Pinho et al., On longitudinal compressive failure of carbon-fibre-reinforced polymer: from unidirectional to woven, and from virgin to recycled, *Philosophical Transitions of the Royal Society A*, Vol. 370, Issue 1965, 2012, 1871-1895; R Gutkin et al., On the transition from shear-driven fibre compressive failure to fibre kinking in notched CFRP laminates under longitudinal compression, *Composites Science and Technology*, Vol. 70, Issue 8, 2010, 1223-1231.

Hierarchical solution



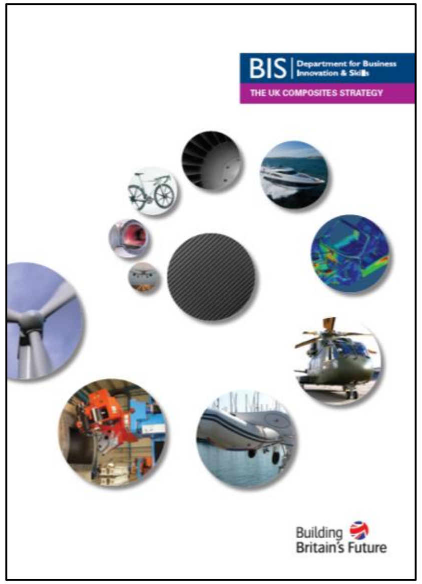
Source: UGK Wegst et al., Bioinspired structural materials, *Nature Materials*, Vol. 14, 2015, pages 23-36.

PROGRAMME GRANT

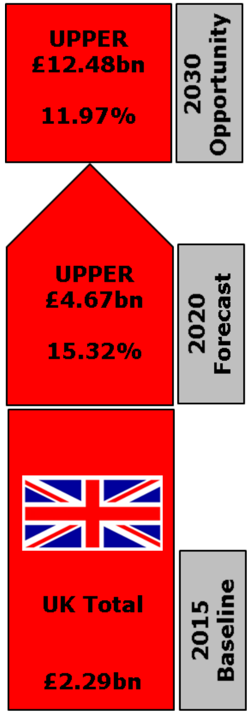
EPSRC mechanism to provide flexible funding to world-leading research groups to address a significant major research challenge:

- Support world leading researchers, bringing together ‘best with best’ teams to tackle a strategic research theme.
- Interdisciplinary and collaborative, requiring the expertise of a number of internationally-recognised scientists or engineers.
- Programme Grants can be awarded for up to a six year duration.

Builds on the connections established during the successful Imperial-Bristol “High Performance Ductile Composite Technology (HiPerDuCT)” programme (hiperduct.ac.uk).



UK composite strategy



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NextCOMP and Industrial Partners

Industrial Partners Group (IPG)

Chair Dr E. Garcia, CTO, NCC

- Sub-group of External Advisory Board
- Provide feedback on impact strategy, industry uptake and regulatory aspects
- Engage with Industrial Workshops and other impact activities
- Identify and promote opportunities for technology transfer at higher TRLs

→ Identification of commercial and impact opportunities for impact investment →

Impact Activities

Industrial demonstrators

- Software / components / protocols

Knowledge exchange

- Annual meetings, scientific conferences, publications

Outreach activities

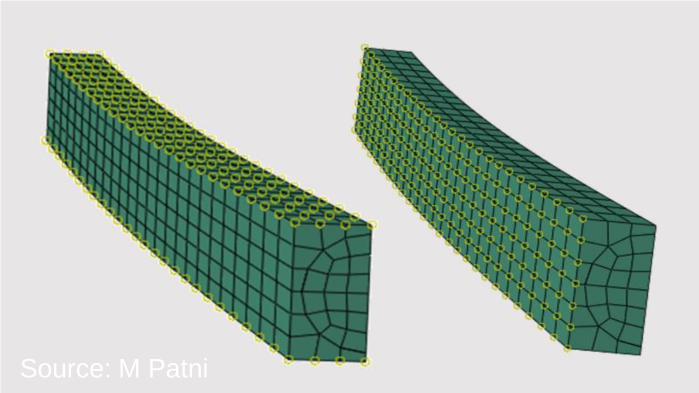
- e.g. Imperial & Cheltenham Festivals, Festival of Nature and FUTURES

Industrial partners provide

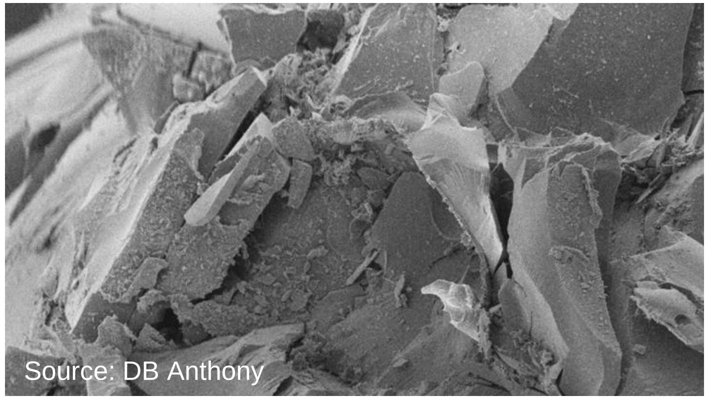
1. **Context:** Current industrial solutions, historical approaches, key application challenges in compression, key performance indicators.
2. **Materials: Constituents, composites [physical contributions welcome]**.
3. **Testing: Key properties and protocol [in kind contribution via testing or facility access welcome]**.
4. **Industrial demonstrators:** Materials, Component definition, Software, Testing Protocols/Regulation.
5. **Knowledge transfer/exchange:** Routes for exploitation for technology transfer at higher TRLs.
6. **Future research collaboration:** co-funding of PhDs, research consortia, Knowledge Transfer Partnerships / Innovate UK activities.

Enquiries from additional potential partners welcome.

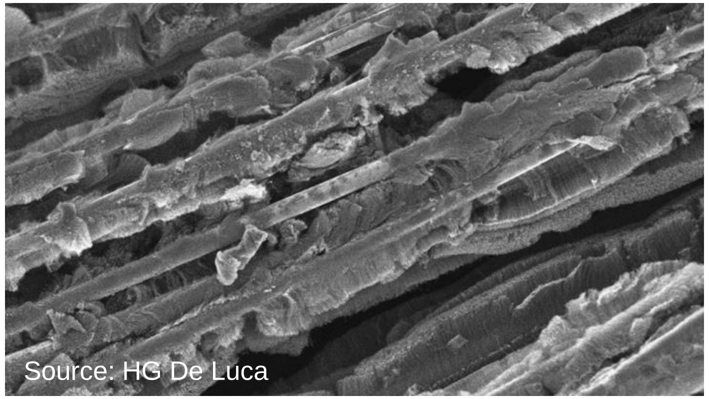
NEXT GENERATION FIBRE-REINFORCED COMPOSITES: A FULL SCALE REDESIGN FOR COMPRESSION



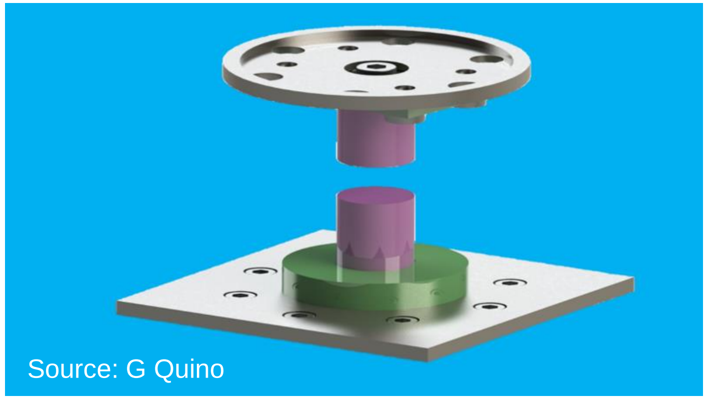
Mechanistic modelling



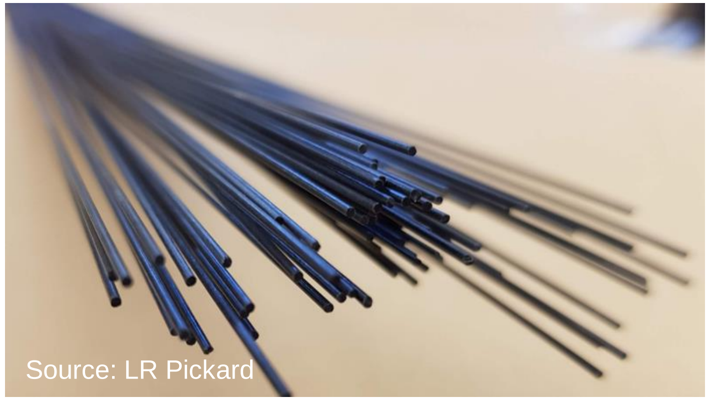
Resin systems



Fibre platforms



In-Situ mechanistic studies

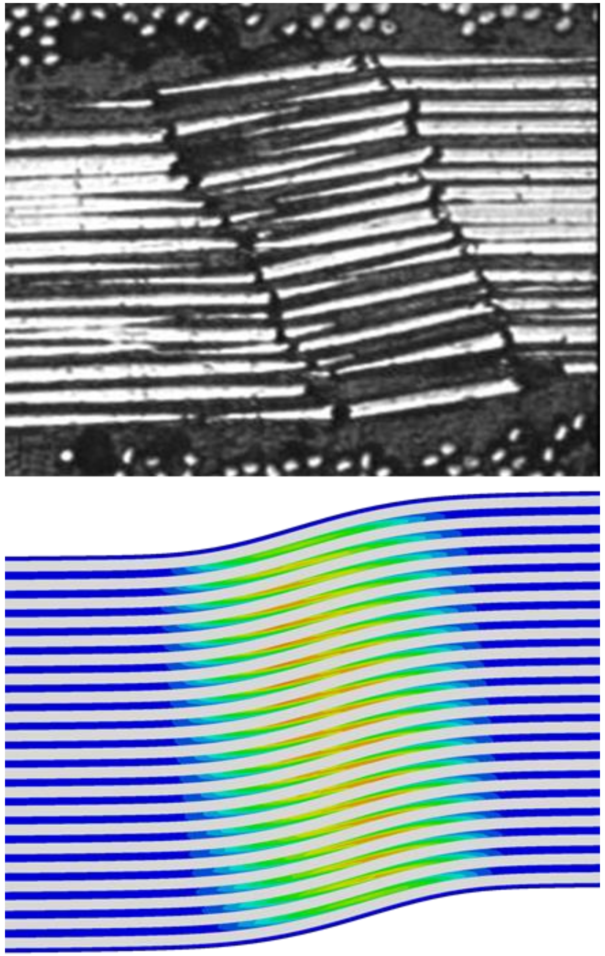


Bundle systems

Ply level systems

Mechanistic modelling

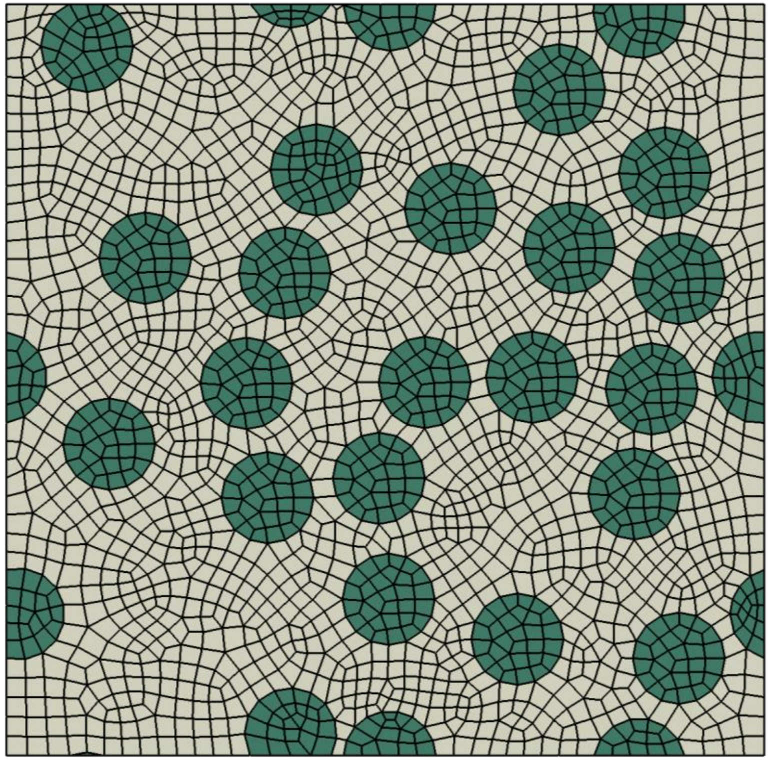
- We model composite behaviour using the detailed constituent properties of the resin, fibres, and their interphase, rather than (global) composite properties.
- Where key constituent properties are missing from the literature, they are determined experimentally.
- Unified analysis using this methodology allows consideration of fibre compression and bending stresses, whilst varying fibre alignment/waviness and the matrix constraints independently.
- Results on the initiation of compressive failure confirms that fibre kinking is the dominant failure mechanism in many state of the art unidirectional composites and precedes elastic micro-buckling.
- The models predict routes to improve the overall composite compressive performance by increasing the fibre volume fractions, matrix-fibre interface, and the matrix shear/modulus properties.



Source: (Top) ST Pinho et al., Fracture toughness of the tensile and compressive fibre failure modes in laminated composites, *Composites Science and Technology*, Vol. 66, Issue 13, 2006, pages 2069-2079. (Bottom) D Bikos.

Mechanistic modelling

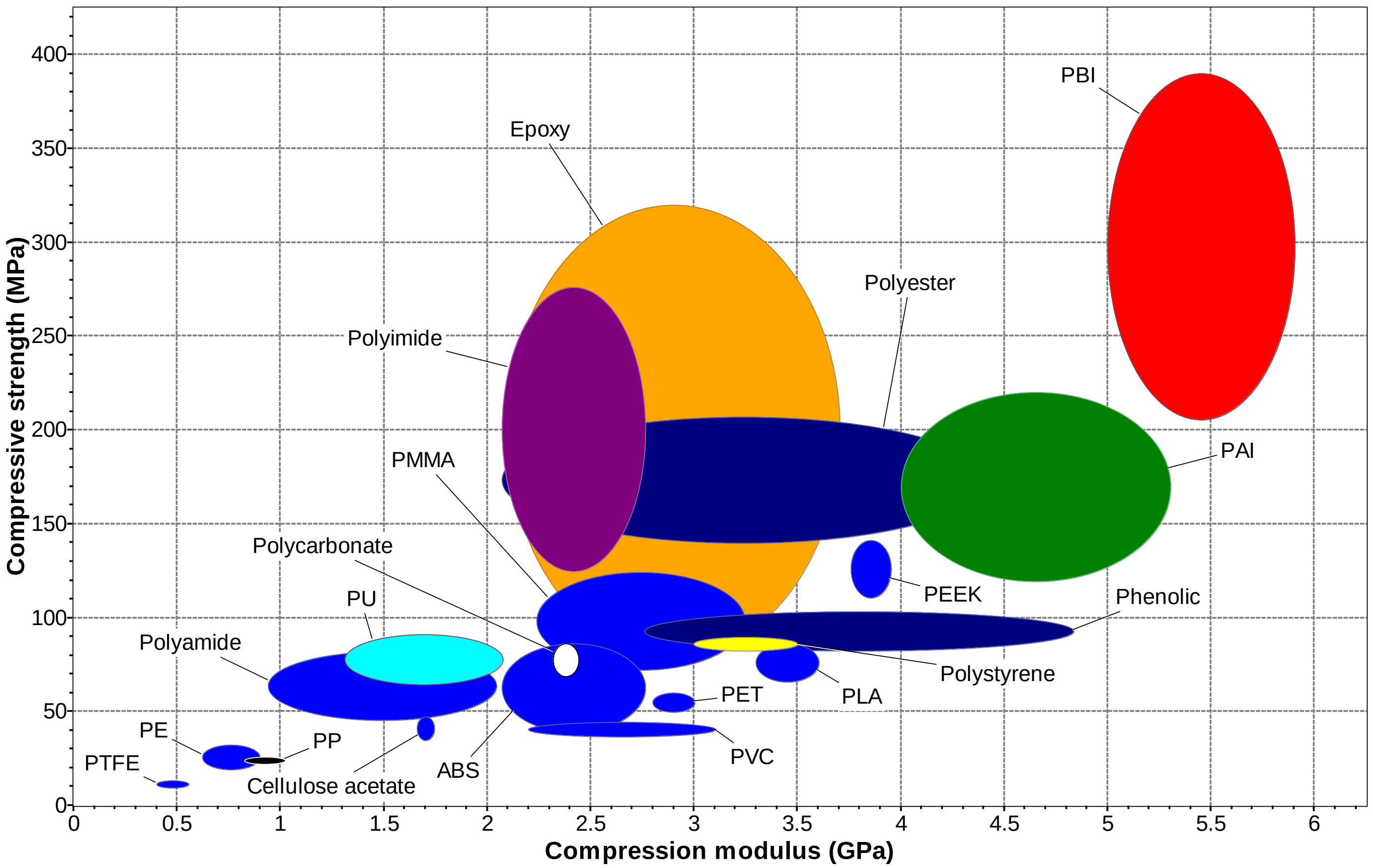
- Since the performance of composites in compression is an intrinsically hierarchical problem, we are building models across a variety of length length scales, from the micro-, meso- to macro.
- Both analytical and micromechanical finite element models are useful for single and multi-fibre systems.
- The introduction of realistic (imperfect) microstructures is included to capture kink-band initiation and propagation.
- However, non periodic boundary condition models negatively impact computational costs. Hence, we are developing new strategies to increase simulated lengths scales more efficiently.



Source: D Bikos.

Resin systems

- Resin systems play a definitive role in stabilising shear instabilities that develop between the fibres during compression.
- Information on the shear strength and shear modulus, as well as the mixed mode compression-shear performance, is extremely scarce for conventional matrix materials.
- Identifying existing matrices with exceptional shear performance is key to delaying kink-band formation, one important route to improved composite compression performance.
- We are exploring routes to produce new high shear/modulus matrix systems, functionalising commercial matrices, adding nanoreinforcements, and synthesising more radical new architectures.



Source: J Gargiuli.

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RESIN SYSTEMS

- To facilitate detailed matrix shear-compression characterisation, new sample geometries have been developed, in both shear and compression, that can be applied to a range of systems, including:
    - Commercial resins.
    - New in-house model systems.
    - New matrix concepts.

- The resulting shear-compression data are being mapped using updated Ashby plots and the resulting constitutive properties implemented in the computational modelling frameworks.

- The combination of detailed testing and modelling has allowed new key performance indicators to be identified, for example, the resin dilation angle.

Source: G Quino.

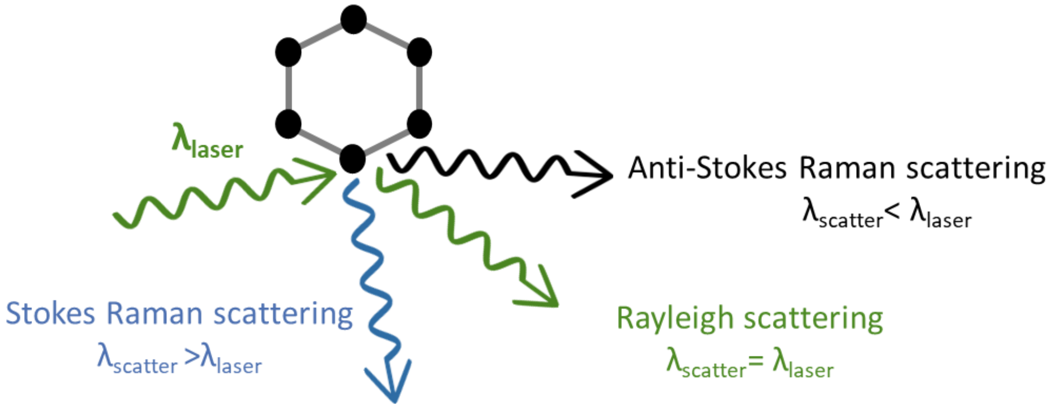
FIBRE PLATFORMS

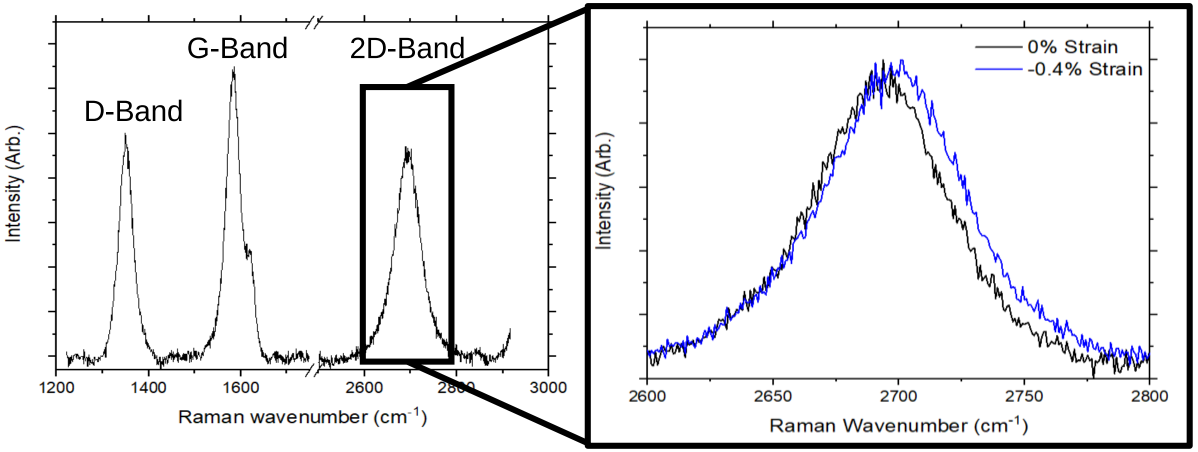
- The shape and form of high performance (non-natural) fibres have usually been chosen for improved tensile properties; typically they are uniform, continuous, circular, and small in diameter (~5-20 μm), but these characteristics may not be optimal for compressive loads.

- Characterisation of fibre constitutive properties, relevant to compression, is limited by the challenges of direct measurements on single fibres and the non-linearity of (carbon) fibre compression moduli.

- Single fibre compression characterisation using Raman spectroscopy is able to characterise (Raman active) fibre stiffness, strength, and stress-transfer across interfaces.

- Commercial fibres are being surveyed to identify the most promising examples, parameterise the computational models and predict possible performance improves in more complex multi-fibre composite systems.





Source: C Woodgate.

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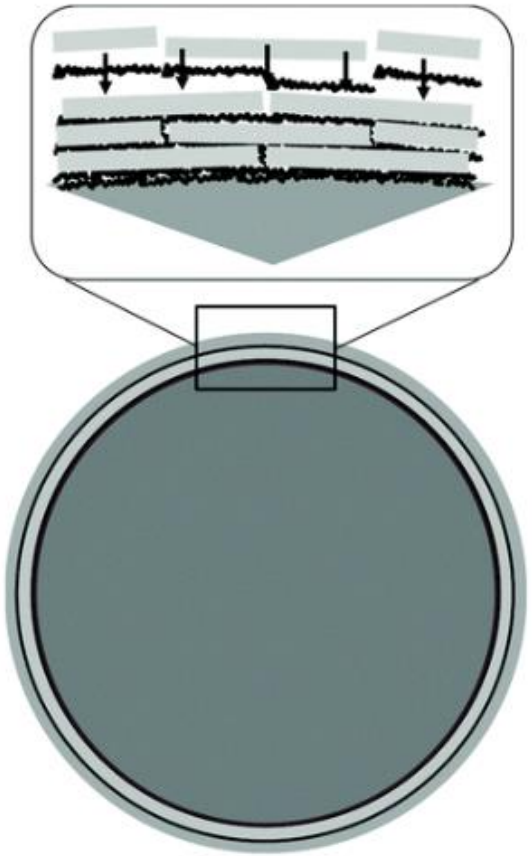
Fibre platforms

- Whilst it is beyond of the scope of the programme to fabricate new high performance fibres, the introduction of lateral supporting motifs within the interphase region is a promising avenue to delay fibre kink-band formation whilst avoiding debonding.

- Utilising hierarchal principles, nanostructured architectures can be added into the critical interphase regions. Such structures are inspired by biological systems that exhibit high stiffness and high strength, whilst also increasing toughness. However, they must be quantitatively re-designed to address the local loading environment in composites.

- Model fibre systems are studied using both Raman spectroscopy and a newly designed bundle composite test, to characterise their properties through a range of length scales from single fibres to multi-fibre tows.



Source: F De Luca et al., Increasing carbon fiber composite strength with a nanostructured “brick-and-mortar” interphase, *Materials Horizons*, Vol. 5, Issue 4, 2018, pages 668-674.

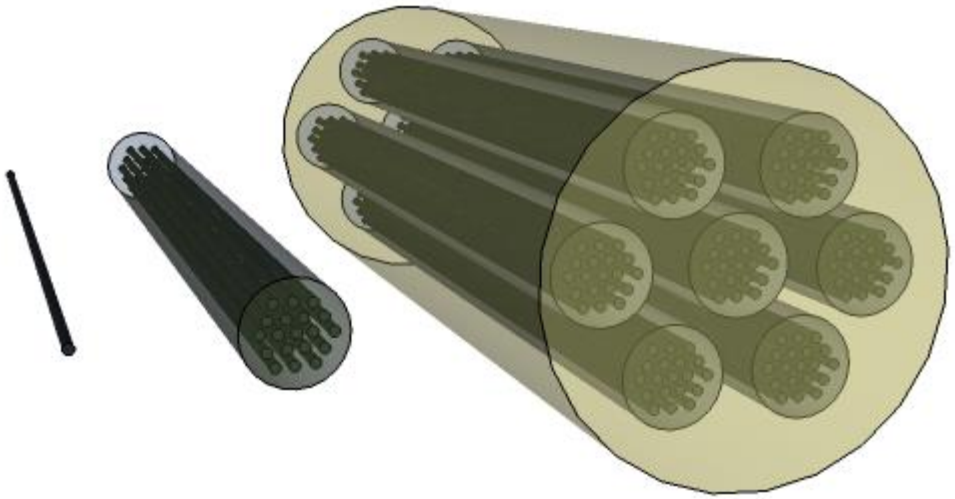
Bundle systems

- Larger bundle-like systems, for instance rods or struts, are a great opportunity to investigate highly aligned fibres/matrix systems at a smaller scale than full laminated structures.

- Bundles/rods can be produced in-house though pultrusion, or obtained commercially, then modified and combined to produce struts designed to explore new mechanisms.

- The bundle-of-bundles concept allows a different matrix to used within each unidirectional rod and between them. In addition, the rod cross-section and fibre types can be hybridised within the larger composite struts.

- A variety of bundle-of-bundle properties are being explored. Some are analogous to the lateral support motifs proposed for individual fibres but applied at larger scales.



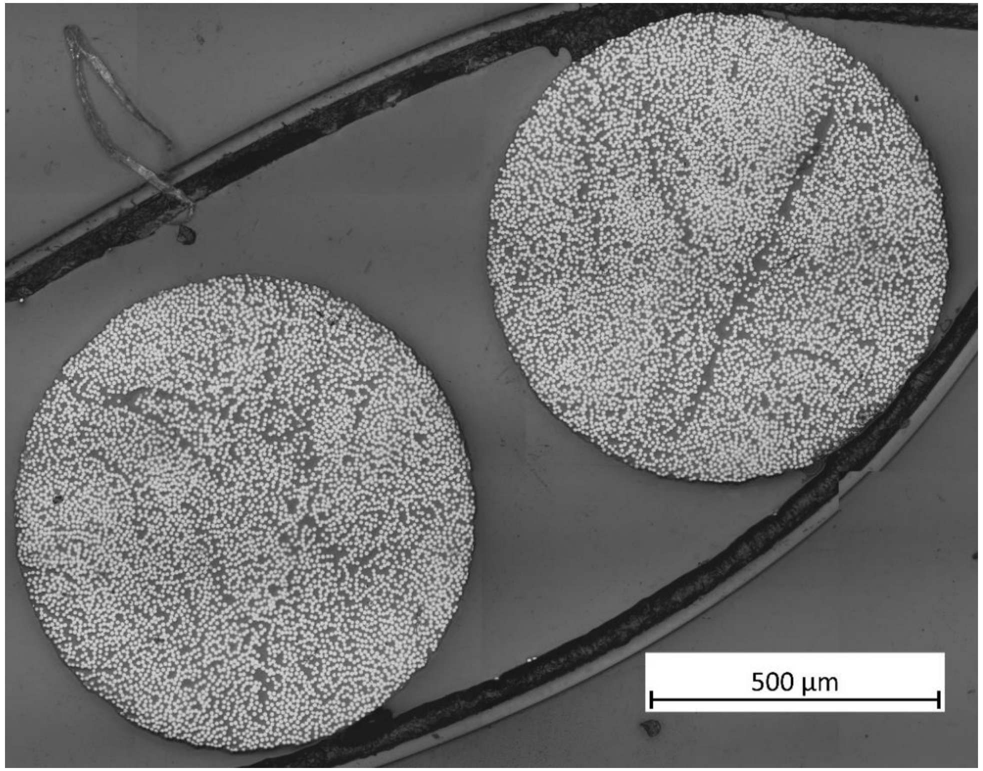
Source: DB Anthony et al., Hierarchical solutions to compressive problems in fibre-reinforced composites, *Proceedings of the 20th European Conference on Composite Materials (ECCM20)*, June 2022, Lausanne, Switzerland [modified].

BUNDLE SYSTEMS

- Over-braiding or wrapping can be implemented to increase lateral support in bundle composites, by locating an individual rod within the braiding locus.

- At one higher level of hierarchy, bundles of braided rods can be combined to form a strut that is then over-braided in the same fashion.

- The key challenges relate to process design to ensure full matrix infusion whilst retaining alignment.



Source: LR Pickard et al., Manufacturing of pultruded rod based hierarchical composite structural members, *Proceedings from International Conference on Manufacturing of Advanced Composites 2022 (ICMAC)*, September 2022, Sheffield, UK.

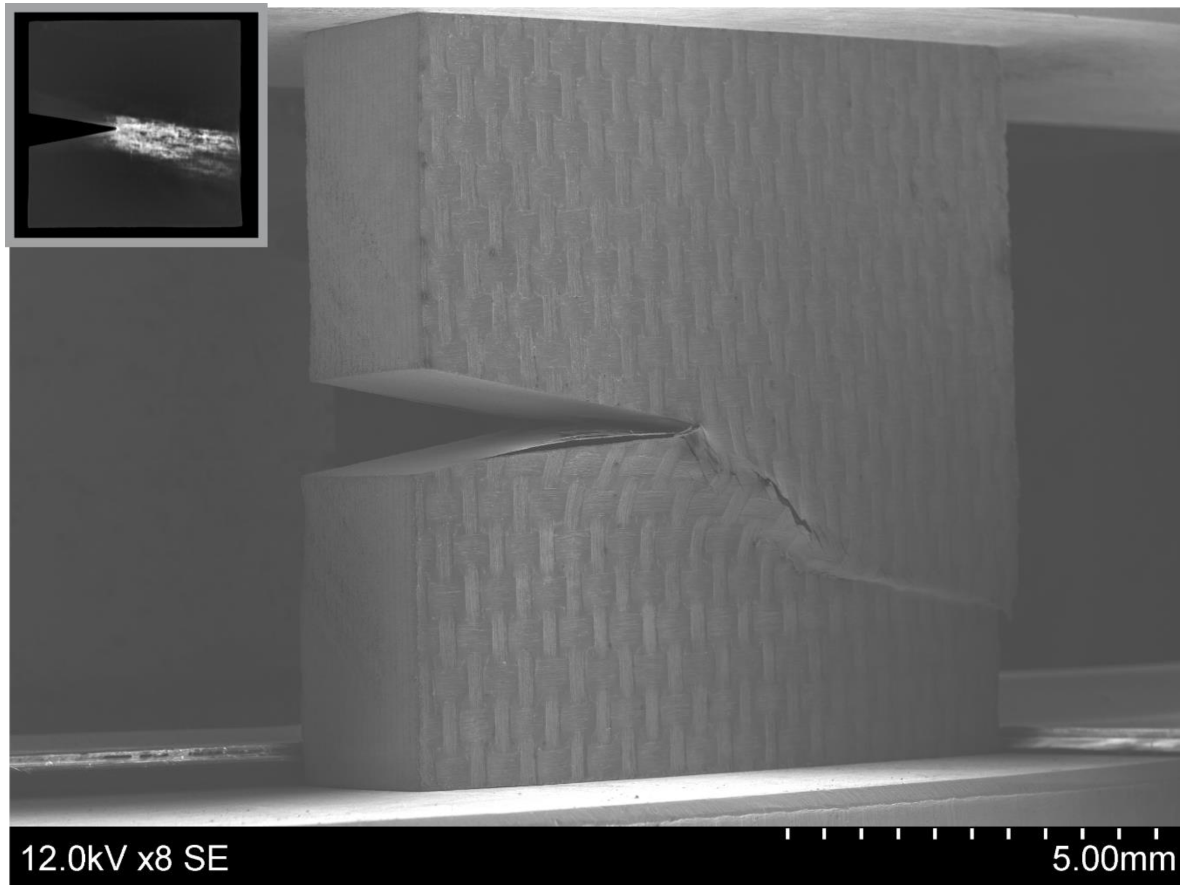
Ply systems

- In natural layer structures, deformation and localised failures modes are promoted to limit damage progression into the whole system.

- In the NextCOMP ply level systems, we mimic this response using high performance materials. The objective, to control, or arrest the propagation of failure (kink-bands), and in turn reduce high stress states that lead to composite failure.

- The fibre distribution within a ply can be carefully designed to alter and manipulate the failure modes (e.g. reducing stress concentrations from crack tips).

- With careful control over composite architectures and materials, in- and out-of-plane, there is the potential to localise kink-band damage producing a material which fails progressively rather than catastrophically.

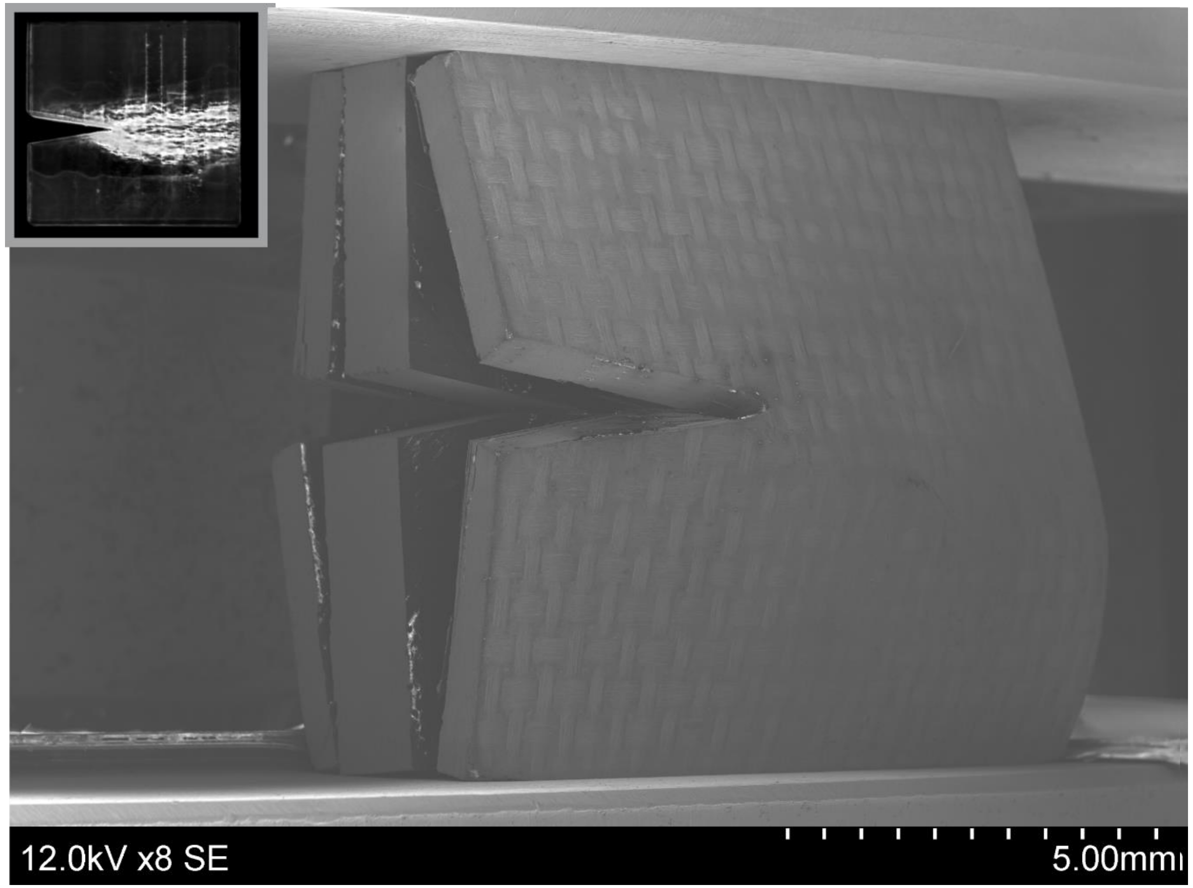


Source: T Garulli.

PLY SYSTEMS

- The combination of existing (semi-)commercial materials in precise lay-ups allows the exploration of new concepts and the production of composites with improved compressive performance.

- More fully hierarchical systems will be implemented by combining hierarchical fibre-level systems with ply or rod scale architectures, in order to maximise the overall response.

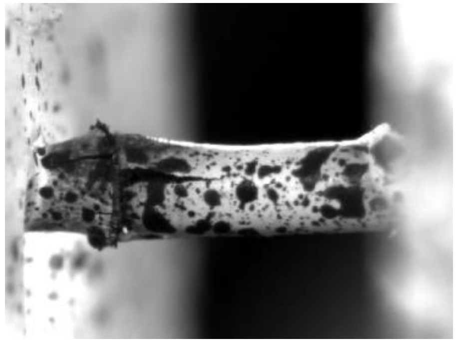


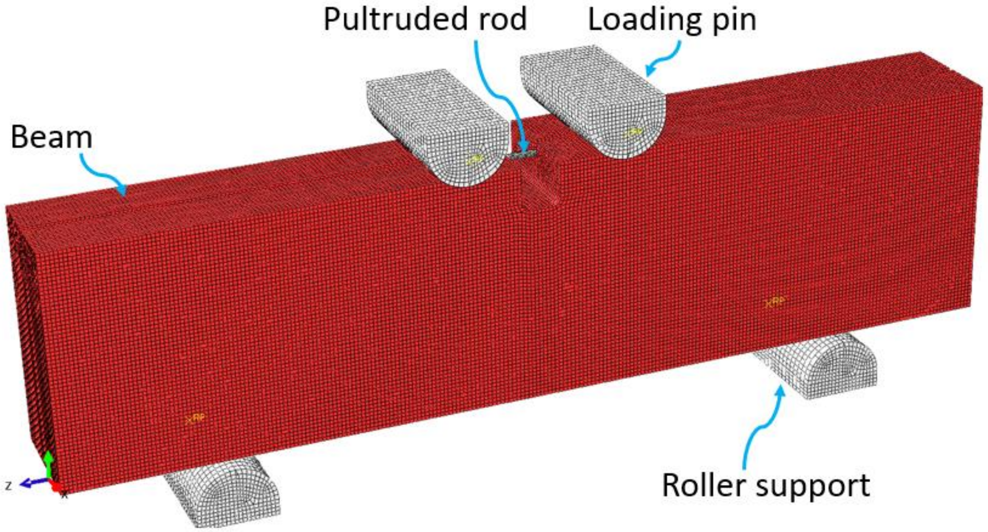
Source: T Garulli.

IN-SITU MECHANISTIC STUDIES

- NextCOMP's investigations have highlighted the need for new test methods including approaches to:
  - Obtain missing matrix and fibre properties needed for predictive modelling.
  - Validate and characterise small, bundle-like tests, to illustrate new mechanisms.
  - Explore small coupons for which no suitable characterisation method, or standard, currently exists.

- Examples of new test methods include:
  - Modification of a 4-point bending test to determine the compressive behaviour of rod or bundle-like specimens (tow scale).
  - Matrix shear, and shear under compression tests including the determination of dilation angle of resin systems.





Source: G Quino et al., Design of a bending experiment for mechanical characterisation of pultruded rods under compression, *Proceedings of the 20th European Conference on Composite Materials (ECCM20)*, June 2022, Lausanne, Switzerland.

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IN-SITU MECHANISTIC STUDIES

- In addition to the development of new test methods, a review of the existing testing standards has been made.

- A composite compression test procedure, previously developed within Imperial College London, and widely applied, has no easily accessible formal documentation. As part of the NextCOMP programme, the Imperial College Compression Standard protocol will be updated an addendum to the existing technical memo released ca. 1991.

- A variety of demonstrator pieces have been considered. In discussion with the industrial partners, one key target for larger scale implementation of new ply architectures is the ASTM D6484 Open Hole Compressive Strength of Polymer Matrix Composite Laminates.

Source: Instron, Composites Testing Solutions: Composite fixtures, Boeing Open Hole Compression Fixture, page 12, CompositesTesting_BrochureV1, 2021.

WORKSHOPS

- We have been delighted with the discussions which have come from our internal and external workshops.
- Topics have included “*Initiation in unidirectional composites”*, “*Propagation in multidirectional composites*”, and “*Industrial technology requirements*”.
- We are looking to add additional workshops in the near future. If you are interest in engaging with NextCOMP programme through these workshops please contact us.

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- NextCOMP website - includes all our latest news & invited lectures and links
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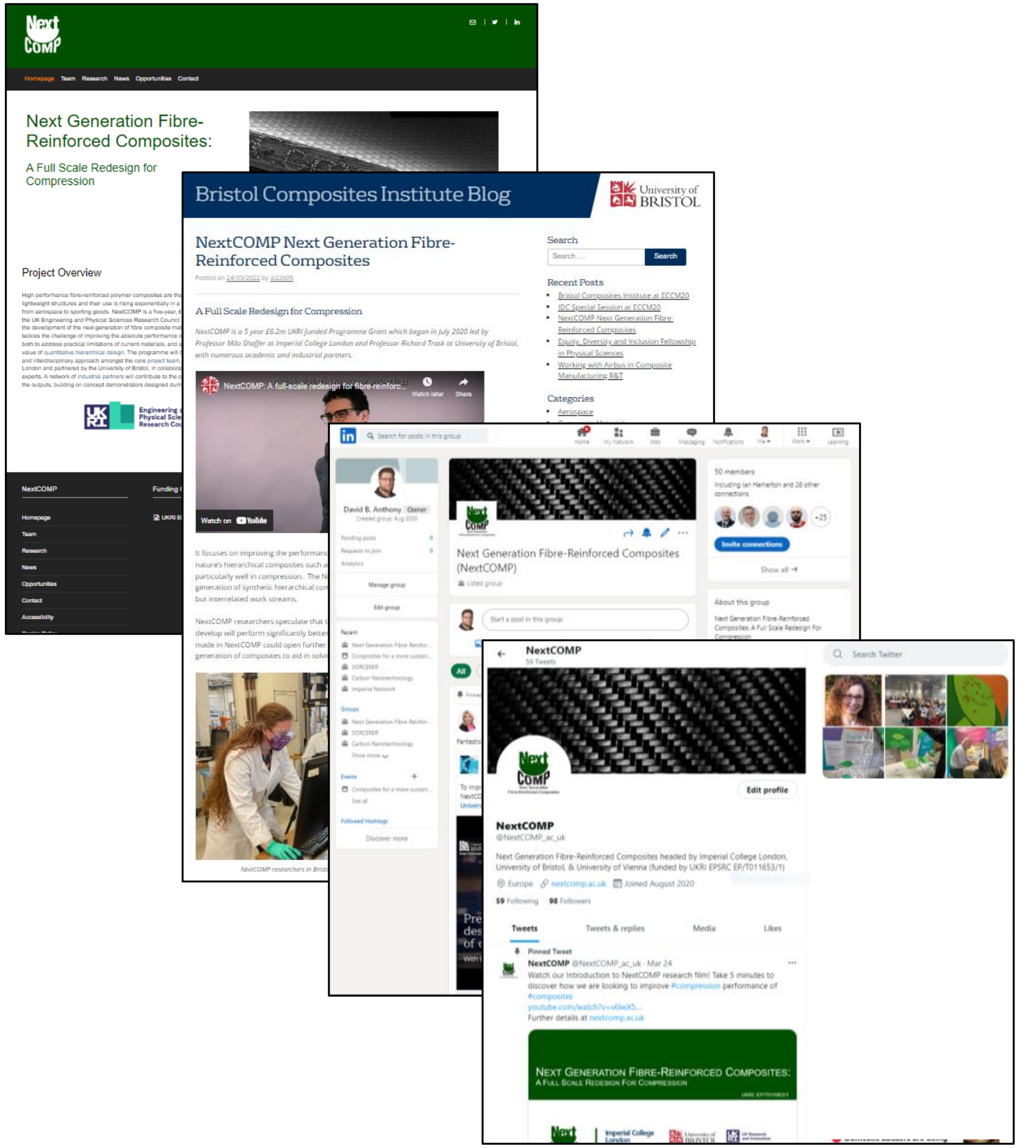
- Email
  info@nextcomp.ac.uk



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We would like to acknowledge funding which supported this work from the UK Research and Innovation - EPSRC Programme Grant; Next Generation Fibre-Reinforced Composites: A Full Scale Redesign for Compression (EP/T011653/1)

A collaboration between Imperial College London and University of Bristol

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