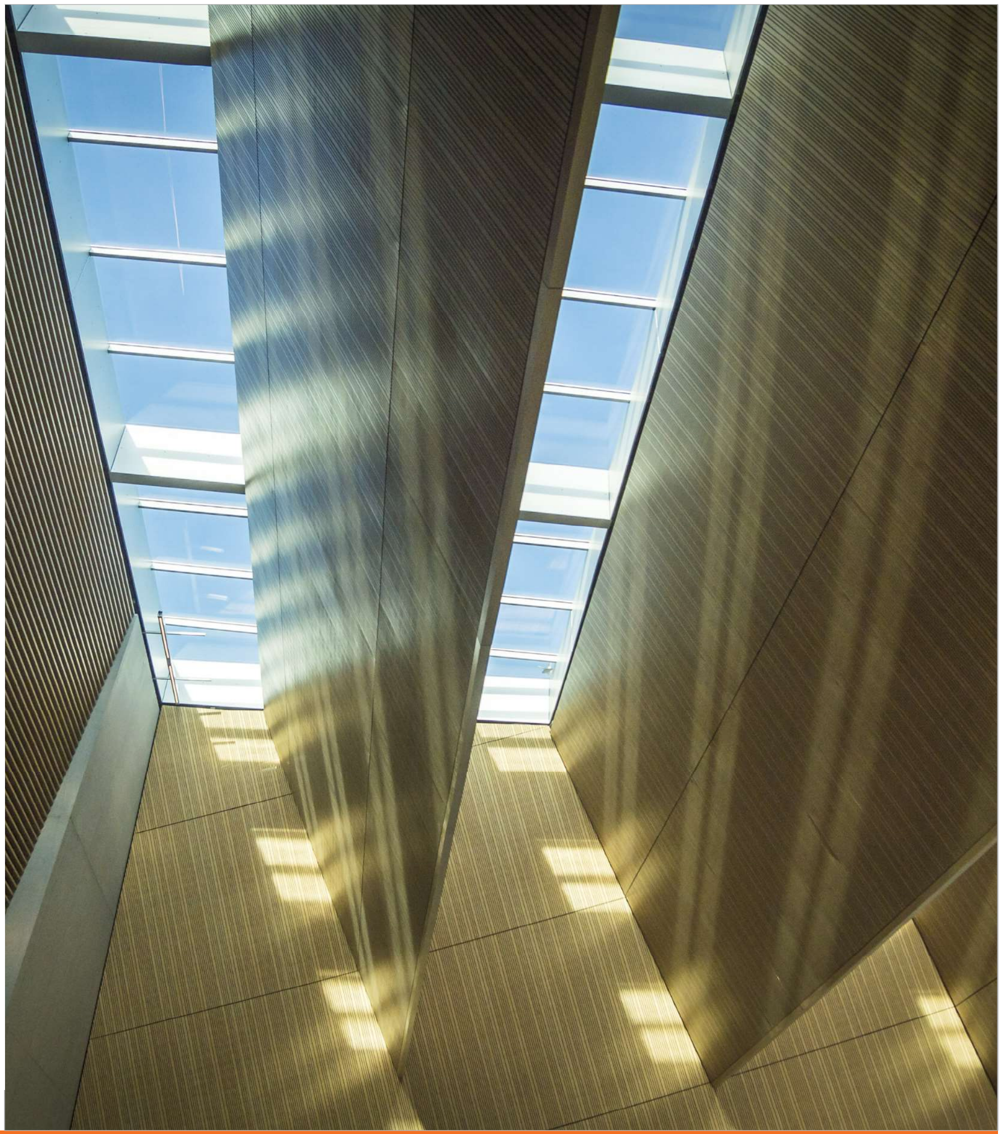
ECCM 20

26–30 JUNE

2022

LAUSANNE

SWITZERLAND



Proceedings of the 20th European Conference on Composite Materials

COMPOSITES MEET SUSTAINABILITY

Vol 1 – Materials

Editors : Anastasios P. Vassilopoulos, Véronique Michaud

Organized by :

EPFL

Under the patronage of :

CCLAB Composite Construction Laboratory

LPAC Laboratory for Processing of Advanced Composites

ESCM EUROPEAN SOCIETY FOR COMPOSITE MATERIALS

ECCM
20
26-30 JUNE
2022
LAUSANNE
SWITZERLAND

EPFL

CCLAB
Composite
Construction
Laboratory

LPAC
Laboratory for Processing
of Advanced Composites

Proceedings of the 20th
European Conference on Composite Materials
ECCM20
26-30 June 2022,
EPFL Lausanne Switzerland

Edited By :

Prof. Anastasios P. Vassilopoulos, CCLab/EPFL
Prof. Véronique Michaud, LPAC/EPFL

Oragnized by:

Composite Construction Laboratory (CCLab)
Laboratory for Processing of Advanced Composites (LPAC)
Ecole Polytechnique Fédérale de Lausanne (EPFL)

ECCM
20
26-30 JUNE
2022
LAUSANNE
SWITZERLAND

ISBN: 978-2-9701614-0-0
DOI: http://dx.doi.org/10.5075/epfl-298799_978-2-9701614-0-0

Published by :

Composite Construction Laboratory (CCLab)
Ecole Polytechnique Fédérale de Lausanne (EPFL)
BP 2225 (Bâtiment BP), Station 16
1015, Lausanne, Switzerland

https://cclab.epfl.ch

Laboratory for Processing of Advanced Composites (LPAC)
Ecole Polytechnique Fédérale de Lausanne (EPFL)
MXG 139 (Bâtiment MXG), Station 12
1015, Lausanne, Switzerland

https://lpac.epfl.ch

Cover:

Swiss Tech Convention Center
© Edouard Venceslau - CompuWeb SA

Cover Design:

Composite Construction Laboratory (CCLab)
Ecole Polytechnique Fédérale de Lausanne (EPFL)
Lausanne, Switzerland

©2022 ECCM20/The publishers

The Proceedings are published under the CC BY-NC 4.0 license in electronic format only, by the Publishers.

The CC BY-NC 4.0 license permits non-commercial reuse, transformation, distribution, and reproduction in any medium, provided the original work is properly cited. For commercial reuse, please contact the authors. For further details please read the full legal code at http://creativecommons.org/licenses/by-nc/4.0/legalcode

The Authors retain every other right, including the right to publish or republish the article, in all forms and media, to reuse all or part of the article in future works of their own, such as lectures, press releases, reviews, and books for both commercial and non-commercial purposes.

Disclaimer:

The ECCM20 organizing committee and the Editors of these proceedings assume no responsibility or liability for the content, statements and opinions expressed by the authors in their corresponding publication.

Editorial

This collection gathers all the articles that were submitted and presented at the 20th European Conference on Composite Materials (ECCM20) which took place in Lausanne, Switzerland, June 26-30, 2022.

ECCM20 is the 20th edition of a conference series having its roots back in time, organized each two years by members of the European Society of Composite Materials (ESCM).

The ECCM20 event was organized by the Composite Construction laboratory (CCLab) and the Laboratory for Processing of Advanced Composites (LPAC) of the Ecole Polytechnique Fédérale de Lausanne (EPFL).

The Conference Theme this year was “Composites meet Sustainability”. As a result, even if all topics related to composite processing, properties and applications have been covered, sustainability aspects were highlighted with specific lectures, roundtables and sessions on a range of topics, from bio-based composites to energy efficiency in materials production and use phases, as well as end-of-life scenarios and recycling.

More than 1000 participants shared their recent research results and participated to fruitful discussions during the five conference days, while they contributed more than 850 papers which form the six volumes of the conference proceedings. Each volume gathers contributions on specific topics:

Vol 1 – Materials

Vol 2 – Manufacturing

Vol 3 – Characterization

Vol 4 – Modeling and Prediction

Vol 5 – Applications and Structures

Vol 6 – Life Cycle Assessment

We enjoyed the event; we had the chance to meet each other in person again, shake hands, hold friendly talks, and maintain our long-lasting collaborations. We appreciated the high level of the research presented at the conference and the quality of the submissions that are now collected in these six volumes. We hope that everyone interested in the status of the European Composites’ research in 2022 will be fascinated by this publication.

The Conference Chairs

Anastasios P. Vassilopoulos, Véronique Michaud

Hosting Organizations

Composite Construction Laboratory (CCLab)
Laboratory for Processing of Advanced Composites (LPAC)
Ecole Polytechnique Fédérale de Lausanne (EPFL)

Venue

Swiss Tech Convention Center (https://www.stcc.ch)

Conference Chairs

Chair : Prof. Anastasios P. Vassilopoulos, EPFL, Switzerland
Co-Chair: Prof Véronique Michaud, EPFL, Switzerland

International Scientific Committee

Prof. Malin Åkermo SE
Dr. Emmanuel Baranger FR
Prof. Christophe Binetruy FR
Prof. Pedro Camanho PT
Prof. Konstantinos Dassios GR
Prof. Brian Falzon UK
Prof. Kristofer Gamstedt SE
Prof. Sotiris Grammatikos NO
Prof. Christian Hochard FR
Prof. Marcin Kozlowski PL
Prof. Stepan Lomov BE
Dr. David May DE
Prof. Stephen Ogin UK
Prof. Gerald Pinter AT
Prof. Silvestre Pinho UK
Prof. Yentl Swolfs BE
Dr. Julie Teuwen NL
Dr. Panayota Tsotra CH
Prof. Wim van Paepegem BE
Prof. Dimitrios Zarouchas NL
Dr. Andrey Aniskevich LV
Prof. Christian Berggreen DK
Dr. Nicolas Boyard FR
Prof. Valter Carvelli IT
Prof. Klaus Drechsler DE
Prof. Bodo Fiedler DE
Dr. Nathalie Godin FR
Prof. Roland Hinterholzl AT
Prof. Ian Kinloch UK
Dr. Thomas Kruse DE
Prof. Theodoros Loutas GR
Prof. Veronique Michaud CH
Prof. Alessandro Pegoretti IT
Prof. Joao Ramoa Correia PT
Prof. Jose Sena-Cruz PT
Prof. Antonio T. Marques PT
Prof. Thanasis Triantafillou GR
Prof. Albert Turon ES
Prof. Anastasios P. Vassilopoulos CH
Prof. Martin Fagerström SE
Dr. Alexandros Antoniou DE
Prof. Lars Berglund SE
Prof. Michal Budzik DK
Prof. Lucas Da Silva PT
Dr. Andreas Endruweit UK
Prof. Mariaenrica Frigione IT
Dr. Larissa Gorbatikh BE
Dr. Martin Hirsekorn FR
Prof. Vassilis Kostopoulos GR
Prof. Jacques Lamon FR
Prof. Staffan Lundstrom SE
Prof. Peter Mitschang DE
Dr. Soraia Pimenta UK
Prof. Paul Robinson UK
Dr. Olesja Starkova LT
Prof. Sofia Teixeira de Freitas NL
Dr. Stavros Tsantzalis GR
Prof. Danny van Hemelrijck BE
Prof. Michele Zappalorto IT
Dr. Miroslav Cerny CZ

Local Organizing Committee

Prof. Anastasios P. Vassilopoulos, EPFL
Prof. Véronique Michaud, EPFL
Angélique Crettenand and Mirjam Kiener, Lausanne Tourisme

And all those who helped, colleagues who reviewed abstracts and chaired sessions, and CCLab and LPAC students and collaborators who worked hard to make this conference a success.

Sponsors

SHIMADZU
Excellence in Science

Bristol Composites Institute

JEC GROUP

suprem

Surface Measurement Systems
World Leader in Sorption Science

INSTRON®

9T LABS

Anton Paar

DIA-STRON
DELIVERING MEASUREMENT SOLUTIONS

AΞLER

HRC

ICCM 23
INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS
BELFAST 2023
30 JULY - 4 AUGUST

TEIJIN


Functional
Composite
Materials

materials
an Open Access Journal by MDPI

ELSEVIER


frontiers | Research Topics

ECCM Research Topic on Advanced Manufacturing of Composites

Open for submissions ›

Supporting partners

JEC

CertBond
COST Action CA18120

EsSENce

Switzerland Tourism.

SWISS

SBB CFF FFS

sampe
Switzerland

CU
COMPOSITES
UNITED
SWITZERLAND

canton de vaud

Lausanne

Contents

Contribution to the determination of thermal and chemical residual stresses in fiber reinforced composites using the incremental hole drilling method: numerical and experimental approach 1

A novel bio-inspired microstructure for progressive compressive failure in multidirectional composite laminates 7

Fluorescent marking of fibre reinforced plastic for component and material identification in the context of material flow canalization 14

Electrofusion welding of thermoplastic composite pipes 22

Mechanical characterisation of a long discontinuous fibre reinforced composite to evaluate the recycling potential of carbon fibre in structures 29

The mass production of MWCNTS/epoxy scaffolds using lateral belt-driven multi-nozzle electrospinning setup to enhance physical and mechanical properties of CFRP 37

Thermo-mechanical modelling of UD composites to investigate self-heating and thermal softening effect of polymer matrix 43

Towards the development of LDPE multi-layered packaging films with enhanced bioactivity 51

Investigation of 3D printed polymers and moulded composites in hot concentrated acid 59

The effect of resorcinol bis(diphenyl phosphate) on the flammability and flexibility of flame retarded epoxy gelcoats 67

Carbon and glass SMC hybrids in a sandwich arrangement 75

Investigating the effect of interface angle and ply thickness on mode II delamination behaviour of carbon/epoxy laminated composites 82

Ranking the influence of key uncertainties in the curing of thermoset laminates 90

Investigation of the mechanical properties of fuzzy CNT and CNT/CNC integrated glass fiber/epoxy composites with different reinforcing strategies 98

Mechanical properties of epoxy/carbon fiber composite fabricated by filament winding under monotonic and fatigue loadings 106

Thermoset polymer scaling effects in the microbond test 114

Ply orientation effects in multidirectional carbon/epoxy open-hole specimens subjected to shear loading 122

Carbon fibre foams: internal structure and mechanical properties 128

Study on the mode I fracture toughness of composite laminates based on the correlation between AE signal and crack front shape 136

The influence of production wastes incorporation on the properties of thermoplastic matrices . . . 144

Extended failure models for global and local analyses of composite aerostructures 152

High strain rate characterization of twill woven carbon-polyamide laminate in longitudinal compression 160

Damage characterisation in open-hole composites using acoustic emission and finite element, validated by x-ray ct 167

An investigation on the mechanical properties of SPCS 175

Hybrid testing for composite substructures 183

Mechanical characterization of 3R-repairable composites and 3R bonding techniques produced by different processes and their repair efficiency 188

A study to improve the efficiency of laminated heating module for electric vehicles 195

Flexural behaviour of polyurethane foam filled high performance 3-d woven i-beam composites . . 203

Second life for aeronautical manufacturing materials 211

Development of flame retardant coatings for e-caprolactam-based polyamide 6 composites 217

Development of a carbon fiber reinforced sheet molding compound for high temperature applications 225

Development of electric vehicle underbody shield using carbon fiber/poly(ethylene terephthalate) and self reinforced polypropylene composites 233

Sustainable epoxy thermosets with potential applications in the aerospace sector 241

The influence of temperature and matrix chemistry on interfacial shear strength in glass fibre epoxy composites 249

Ceramic spatial structures as a new method of reinforcing ferrous alloys 257

Low velocity impact and residual tensile and compressive strength analysis of carbon fibre SMC composites 263

Influence of TEX linear density on mechanical properties of 3D woven i-beam composites 271

Effect of fiber microstructure on kinking in unidirectional fiber reinforced composites imaged in real time under axial compression 279

Effect of heat/fire on structural damage to carbon fibres in carbon fibre-reinforced composites . . . 287

Use of carbon particles in fiber/epoxy UD laminates 294

Validation of composite aerostructures through integrated multi-scale modelling and high-fidelity substructure testing facilitated by design of experiments and BAYESIAN learning 302

Easy-repairing of high performance fibre reinforced composites with multiple healing cycles and integrated damage sensing 306

The effect of short carbon fibers on viscoelastic behavior of UHMWPE 314

Development of polypropylene melt-blown fine fiber interleaved single-polypropylene composites . 322

Tailored out-of-oven curing of high performance FRPS utilising a double positive temperature coefficient effect 330

Remote activation of frontal polymerization for sustainable manufacturing of thermosets and composites 337

Sustainable multifunctional composites: from energy efficient manufacturing to integrated sensing and de-icing capabilities 344

Improved energy absorption of novel hybrid configurations under static indentation 348

Influence of brazier effect on GFRP thin circular cylinder - an experimental and numerical study . . 354

Multiscale interface behaviour and performance of GF-pc composite 362

Two-dimensional mode II delamination growth in composite laminates with in-plane isotropy . . . 371

Effect of lightweight fillers on the properties of polymer concrete 379

Non linear elastic behaviour of CFRP plies: material or geometrical feature? 387

Evaluation of the shear behavior of PETG/cf and pc/cf coupons manufactured using large-scale additive manufacturing processes 393

3D-print path generation of curvilinear fiber-reinforced polymers based on biological pattern forming 401

Synchrotron radiation 3D computed tomography study on in-situ mechanical damage progression of nanoengineered glass fiber reinforced composite laminates with integrated multifunctionality . . . 408

INSIGTH on induction welding of reactive PMMA carbon fiber composites 415

Litz wire-based multifunctional composites for managing thermal and mechanical loads within electrical systems 423

Shift factor dependence on physical aging and temperature for viscoelastic response of polymers . . 431

Characterization of novel sustainable composite materials based on ELIUM® 188 o resin reinforced with a Colombian natural fiber 439

Combined DIC-infrared thermography for high strain rate testing of composites 447

Effect of gap defects on in-situ AFP-manufactured structures 455

Polypropylene/flax fabric composite laminates: effects of plasma and thermal pre-treatments of reinforcing fibres 463

Improving the delamination bridging behaviour of z-pins through material selection 471

Study on the effect of strain rate and temperature on the mechanical behavior of polypropylene-glass fiber compound and thermoplastic olefin 479

Simultaneous spinning of recycled thermoplastics and glass fibers for hybrid yarns used in sustainable composites 486

Reprocessable vitrimer composites 493

Characterizing the tensile and compressive behavior of PETG/cf and pc/cf manufactured using large scale additive processes 501

Influence of mechanical properties of matrix on bending strength of uni-directional vinyl ester composite 509

Strain sensing of complex shaped 3D woven composites using MXENE nanoparticles 516

Comparison of the fire reaction of a carbon-epoxy composite at small scale and large tests 522

Efficient and versatile 3D woven composite manufacturing: novel approaches on the quality of composite fabrication 532

Electrical conductivity as an instrument for damage diagnostic of nanomodified glass fiber reinforced plastic 539

Out-of-oven manufacturing for natural fibre composites with integrated deformation and degradation sensing 547

Controlling electrical percolation in thermoplastic composites through informed selection of fillers . 555

Macroscale magnetic alignment of multiple discontinuous ferromagnetic fibres in a polymer matrix 563

Laser-induced graphene carbon fiber reinforced composites for multifunctionality 569

Influence of fibre/matrix interface on gas permeability properties of CF/PVDF composites 577

Tribological study on wood and graphene reinforced high density polyethylene 585

Structural health monitoring (SHM) on fibre reinforced composite t-joint geometry manufactured by a novel 3R resin 593

The use of recycled materials towards sustainability: biocomposites manufactured in melt compounding 600

Fully bio-based epoxy-amine resins from circular economy: conception, multiscale structural and mechanical behaviour characterization toward low carbon-footprint composites 608

Mechanism-based assessment of cellulose-based biocomposite cottonid for sustainable construction 616

Novel cellulose based composite material for thermoplastic processing 624

Towards more efficient and environmental friendly flax-based eco-composite through direct F2 fluorination as a compatibilization treatment 632

Flax fibre sizings for fibre-reinforced thermosets - investigating the influences of different sizing agents on fibre moisture content and composite properties 640

Elaboration of hybrid bio-composites with thermoplastic matrix: material formulation and modelling of the quasi-static behaviour 648

Converting recycled glass fibre and polypropylene to feedstock (filament) for material extrusion additive manufacturing 656

Turning oil palm waste into all-cellulose fibreboards utilising refined pulp fibres 662

Soft composites from bio-based resources 668

All lignocellulose biocomposites for woody like materials 675

Dilatometric and fracture mechanism investigations on poly (lactic acid) PLA-calcium carbonate biocomposites 681

Effect of fibrillation of flax mat binder on the impact response of unidirectional flax/epoxy composites and comparison with a glass/epoxy composite 689

Morphological image analysis: a candid technique to determine density and geometric shapes of bio-based fibers and permanent damage due to interaction with water molecules 697

Cost-effective hemp staple fibre yarns for high-performance composite applications 705

Influence of wet/dry cycling on mechanical properties of hemp-reinforced biocomposites 713

Biodegradable polymer films to prevent biofilm formation for food packaging application 721

Life cycle assessment of natural fibre reinforced polymer composites 727

Development of quasi-unidirectional woven fabrics with 100% hemp rovings for composite materials applications 735

Effect of different natural fibres on mechanical and disintegration properties of compostable biobased plastics 743

High-strength rigid boards made from industrially produced bacterial cellulose 750

Manufacturing and mechanical characterisation of unidirectional fique fibres reinforced polypropylene composites 758

Behaviour and repair of flax/ELIUM biocomposites loaded in low velocity impact 766

On the flexural strength and actuation of wood branches – mechanisms useful in composite design? 773

Mechanical modelling of viscoelastic hierarchical suture joints and their optimization and auxeticity 779

Biobased glass fiber sizings for composites in medical and technical applications 788

The effect of humidity on the mechanical properties of flax-polyester biocomposites with different fibre architectures 795

Functionalized wood composites for mechanical energy harvesting and vibration sensing 801

Development of bio-based CFRP laminates for strengthening civil engineering structures 807

Bio-based vacuum infused glass fibre reinforced unsaturated polyester composites for high-performance structural applications 815

Hygrothermal ageing of a GFRP composite produced by vacuum infusion with a novel bio-based unsaturated polyester resin 823

Towards adhesives-free bio-based composites via UV-assisted interfacial cross-linking 831

Towards integrated health monitoring of bio-based composite structures: influence of acoustic emission sensor embedment on material integrity 838

The emerging era of visionary composites by plant-grown matrix and reinforcing fibres: the cellular adhesion 847

Lemongrass plant leaf and culm as potential sources of reinforcement for bio-composites 855

A novel method to quantify self-healing capabilities of fibre reinforced polymers 863

Enabling repairability and reuse of epoxy composites: epoxy vitrimers 871

Low velocity impact response and post impact assessment of healable CFRPS modified with diels-alder resin applied by melt electro-writing process 879

Evaluation of the self-healing capability of a polycaprolactone functionalized interphase for polymer composite applications 887

Highly conductive polypropylene based composites for bipolar plates for polymer electrolyte membrane fuel cells 894

Conductive smart nanocomposite materials for structural health monitoring and motion detection . 901

The effect of conductive network on positive temperature coefficient behaviour for multifunctional composites: from flexible sensing to sustainable manufacturing 909

Graphite filled thermoplastics for thermally conductive pipes 917

Recycling of graphitic bipolar plates for vanadium redox batteries 925

Damage sensing based on electrically conductive nanoparticles in sandwich-structured composites 933

A novel lightning strike protection system comprising an all-polymeric conductive resin 939

Low temperature growth of carbon nanotubes on fibers using copper as catalyst 945

Effect of nanoarchitecture on EMI shielding properties of nanocomposites at high content of graphite nanoplatelets 953

Rapid and facile preparation of multifunctional BUCKYPAPER nanocomposite films 961

Investigation of the thermal and mechanical properties of composite materials with amine-functionalized reduced graphene oxide inclusions 967

The application of coated carbon nanotubes in lightweight metal matrix composites 975

Nanoparticle reinforced lightweight metal composites 981

Self-assembly of NBR and NOMEX via electrospinning: rubbery NANOFIBERS for improving CFRP delamination resistance 986

Chemical compatibilizers as an approach to improve the mechanical properties of poly(propylene) reinforced with graphene nanoplatelets 994

Piezoresistivity of nanocomposites: accounting for CNT contact configuration changes 1002

Ionic polydimethylsiloxane-silica nanocomposites: from synthesis and characterization to self-healing property 1010

Mechanical behaviour of ultrathin carbon nanomembranes for water purification 1018

Intense pulsed light welding process with simultaneous mechanical roll-pressing for highly conductive silver nanowire/polyethylene terephthalate composites 1025

Surface functionalization of quartz fibres by direct growth of carbon nanostructures 1032

Characterisation of graphene-enhanced carbon-fibre/PEEK manufactured using spray-deposition and laser-assisted automated tape placement 1040

High speed imaging of the ultrasonic deagglomeration of nanoparticles in water 1048

Effects of microwave-assisted cross-linking on the creep resistance and measurement accuracy of the coaxial-structured fiber strain sensor 1056

Mechanics of reinforcement of polymer-based nanocomposites by 2D materials 1062

Enhanced mechanical properties of hierarchical MXENE/cf composites via low content electrophoretic deposition 1069

Remote field induced response of polymer nanocomposites embedded with surface-functionalised dielectric nanoparticles 1079

Effects of hybridization and ply thickness on carbon/carbon composite laminates strength and toughness 1091

Effect of weathering on the long-term performance of natural fiber reinforced recyclable polymer composites for structural applications 1097

Fibres hybridization for thermoplastic matrix composites 1104

Mechanical characterization of a three-dimensional hybrid woven composites 1112

Design and characterization of tough architectured ceramic-based composites 1119

Bearing strength high performance fibre metal thin-ply laminates 1127

Visoelastic and VISCOPLASTIC creep modelling of short-glass fibre reinforced polypropylene composites 1130

3D printed short carbon fibres reinforced polyamide: tensile and compressive characterisation and multiscale failure analysis 1137

Estimation of interfacial shear strength of long glass fibre composites by x-ray computed tomography 1145

Material characterisation and fatigue data correlation of short fibre composites: effect of thickness, load ratio and fibre orientation at elevated temperature 1151

Local stress-strain behaviour in short glass fibre reinforced polymers - a comparison of different simulation approaches with experimental results based on x-ray computed tomography data 1159

Effect of fibre orientation, temperature, moisture content and strain rate on the tensile behaviour of short glass fibre-reinforced polyamide 6 1167

A mode II testing method for hybrid composites 1175

Deployable composite meshes – modelling, manufacture and characterisation 1183

Are pseudo-ductile all-carbon hybrid laminates notch insensitive in open hole tension? 1191

Reparability as a new function for high-performance pseudo-ductile hybrid composites 1197

On the optimal design of smart composite sensors for impact damage detection 1205

Impact properties of flax-carbon hybrid composites under low-velocity impact 1213

Enhancement of thin-ply composites translaminar toughness through fiber-hybridization: towards a discrimination with the ply thickness effect? 1220

Assessing the impact behavior of highly aligned fiber hybrid composites 1228

Development and characterization of hybrid thin-ply composite materials 1236

Tensile fatigue performance of carbon-carbon hybrid quasi-isotropic laminate 1244

Variable stiffness lattice structures 1251

Virtual-physical engineering of a graded CFRP/titanium aircraft suspension strut 1258

Manufacturing and properties of hybrid composites of continuous steel and glass fibers made by tailored fiber placement 1266

A novel hybrid thermoset-thermoplastic robot-based production concept for lightweight structural parts: a special view on the hybrid interface 1274

Tensile properties of deep drawn in-situ polymerized fiber-metal-laminates 1282

Micro-scale modelling of composites made of RCF/ PA6 staple fiber yarns with special emphasis on fiber length distribution 1290

Micro-ct based assessment of 3D braided AL2O3 reinforcement uniformity and permeability of all-oxide ceramic matrix composites production processes 1296

Multi-scale modeling of the thermo-viscoelastic behavior of 3D woven composites 1303

Advanced natural fibre textiles for composite reinforcement 1311

Characterization of interlock 3D permeability tensor for c-RTM process 1318

Automated g-code to FE mesh conversion - modelling polymer penetration into a textile to generate a polymer-textile composite made by additive manufacturing 1326

Micro-ct-based numerical validation of the local permeability map for the b-pillar infusion simulation 1333

Effect of temperature on damage onset in three-dimensional (3D) woven organic matrix composites for aero-engines applications 1341

Simulation of frictional contact interactions within jacquard harness of weaving looms for 3D interlock fabrics 1349

Laccase-enzyme treatment of flax fibres for improved interfacial strength in natural fibre composites 1357

DIC-based monitoring on DEBONDING crack propagation in wrapped composite joints 1362

Ultrasoft and hyperelastic electrically conductive nanocomposites for strain sensing applications . . 1369

Mechanical, rheological and thermal evaluation of poly(lactic acid) (PLA) / micro fibrillated cellulose (MFC) plasticized biocomposites produced with flat die extrusion and calendering 1377

Optimization of an exoskeleton 1384

Banana fibre as sustainable and renewable resource for reinforcement of polylactic acid 1391

Hybrid ratio effect on flexural properties for CFRP-natural fiber composite hybrid materials 1398

Investigation of energy absorption capacity of novel 3D-printed glass fibre reinforced thermoplastic bio-inspired structures 1404

Rapid fatigue life prediction of CFRP laminates by combining the data of self-heating with stiffness degradation 1412

Performance evaluation of e-skin for structural deformation detection 1420

Temperature detectable surface coating and self-sensing system with carbon nano-tube/epoxy composites 1426

Solubility behavior of graphene-oxide with various solvents 1433

Biodegradable polymer-based composites filled with biochar for tunable release of carvacrol 1437

Designing bicontinuous silica-epoxy nanocomposites 1445

Robust continuous production of carbon nanotube-grafted structural fibres: a route to hierarchical fibre reinforced composites 1451

Printed circuit boards made from cellulose fibrils 1457

Sandwich type shape memory polymer composite actuators to increase the recovery moment and deformability 1465

Supercritical CO2 assisted foam extrusion for aeronautical sandwich structure manufacturing . . . 1472

Kinetic studies and its influence on phase transition behaviour of multicomponent amine-cured epoxy blend 1480

Non-isocyanate polyurethanes based composites: a new route to sustainable fully biobased structural composites . . . 1486

MXENE nanoparticles to impart multifunctional properties to fibre reinforced plastic composites . . 1495

COMBOO – properties of a novel bamboo based honeycomb core material for composite sandwich structures . . . 1500

Effect of aspect ratio and bulk density of carbon nanotube on the electrical conductivity of polycarbonate/multi-walled carbon nanotube nanocomposites . . . 1508

Hierarchical solutions to compressive problems in fibre-reinforced composites . . . 1512

Tough poly(ethylene glycol)-sized bacterial cellulose sheet for high impact strength laminated acrylic composites . . . 1518

Experimental investigation and modelling of the morphology and induced thermal properties evolution by consolidation of flax fibres hybrid reinforced thermoplastic composite . . . 1526

Avoiding complete failure of composite t-joints by embedding sacrificial cracks inside the BONDLINE 1536

Mechanical analysis of the indentation behavior of short fiber-reinforced composites using finite element method . . . 1542

Micro-scale measurements on epoxy using in-situ microscopic techniques . . . 1549

Study on cure-dependent properties of epoxy molding compound and warpage of semiconductor packages . . . 1557

Thermoplastic coating on carbon fiber for the design of sustainable composite materials . . . 1565

Fabrication of CNT aerogel composite through reactive infiltration of polyamide 6 . . . 1571

Void reduction in graphene interlayer enhanced carbon fibre thermoplastic composites . . . 1579

Highly deformable and processable poly(3-hydroxybutyrate) in presence of FERULIC acid-based additives . . . 1587

Chitosan nanoparticles with ginkgo BILOBA extract in an alginate carrier as a system for the slow release of the active substance . . . 1595

HIERARCHICAL SOLUTIONS TO COMPRESSIVE PROBLEMS IN FIBRE-REINFORCED COMPOSITES

David B Anthony[a,b]*, Cameron G Woodgate*[c]*, Charles MD Shaw*[e]*, Mayank Patni*[d]*,*
Dimitrios Bikos[d]*, Rupam Gogoi*[a]*, Torquato Garulli*[b]*, Laura R Pickard*[c]*, Gustavo Q Quino*[c]*,*
Joseph F Gargiuli[c]*, Soraia Pimenta*[d]*, Giuliano Allegri*[c]*, Silvestre T Pinho*[b]*, Ian Hamerton*[c]*,*
Emile S Greenhalgh[b]*, Stephen J Eichhorn*[c]*, Paul Robinson*[b]*, Michael R Wisnom*[c]*, Richard S Trask*[c]*,*
Milo SP Shaffer[a,e]

a: Department of Chemistry, Imperial College London, UK
b: Department of Aeronautics, Imperial College London, UK
c: Bristol Composites Institute, Department of Aerospace Engineering, University of Bristol, UK
d: Department of Mechanical Engineering, Imperial College London
e: Department of Materials, Imperial College London, UK

d.anthony08@imperial.ac.uk

Abstract: *Currently, the useable compressive properties of a composite are restricted by set design limits well below the expected intrinsic performance of the materials contained within. The next generation of high-performance fibre-reinforced polymer composites will need to address the challenge of improving the absolute performance of composites in compression. This task requires a rethink of the whole system; not only to address practical limitations of current materials, but their combination, interface, and their architecture. The mechanisms involved do not simply act over the nano-, macro-, or meso-level independently, but are mutually related at the system level, complicating the approach.*

Keywords: Hierarchical; Compression; Fibre-reinforced composites

1. Introduction

In natural materials, such as wood and bone, a hierarchical framework is employed with precise structural features at all lengthscales [1]. Whilst this level of intricacy is still beyond current composite production, similar motifs can be made from intrinsically superior constituents, in order to improve (artificial non-natural) composite compression response. This hierarchical approach, with new constituent materials, and advanced assembly processes, when coupled with digital sandboxes, permits a fresh look at the failure mechanisms, providing opportunities to redirect, or suppress, failure modes to improve overall composite performance. The problem can be broken down into a number of interconnected components with attention given to the fibres, matrix and their interface/interphase, the design and lay-up of these constituents, and investigations using new analytical frameworks. This paper will outline the fibre-reinforced compressive weaknesses and approaches to resolve them, providing an insight into current state-of-the-art hierarchical composites.

©2022 Anthony et al. doi:10.5075/epfl-298799_978-2-9701614-0-0 published under CC BY-NC 4.0 license

2. Fibre-reinforced composites and bio-inspiration for hierarchical motifs

Fibre-reinforced composite materials are prominent in a range of applications with tensional loading conditions demonstrating their greatest performance (in the fibre axis). Whilst fibre-reinforced composites are used in other loading conditions, their compressive strength is approximately 60% of their tensile strength. Composite failure does not depend on a single element but rather a complex interconnectivity between the fibres, matrix, their interface, and the architecture of the specimen. In some instances, improving one area, for instance a high interface matrix-fibre adhesion, alters the failure mode of the composite e.g. inducing cohesive matrix failure, which can be an undesirable mechanism leading to a lower ultimate composite performance. For these reasons a holistic approach to address the compressive weakness in composites is sought with hierarchical architectures an intriguing approach to solve the weakness observed in compression. Looking to nature for inspiration [2, 3], a number of quite different approaches are observed; for example, multiscale reinforcing elements with particular orientation and support (Figure 1) [4], systems that have a strut and skeletal formation with minimal matrix content (fibrous), or conversely brick-and-mortar (layered) like formations using short reinforcing structures that dissipate stresses within the system, amongst other motifs. Alternative methods to dissipate energy or impacts through shear stiffening responses in the bulk of the material are observed but not commonly associated with a fibre-like scaffolds.

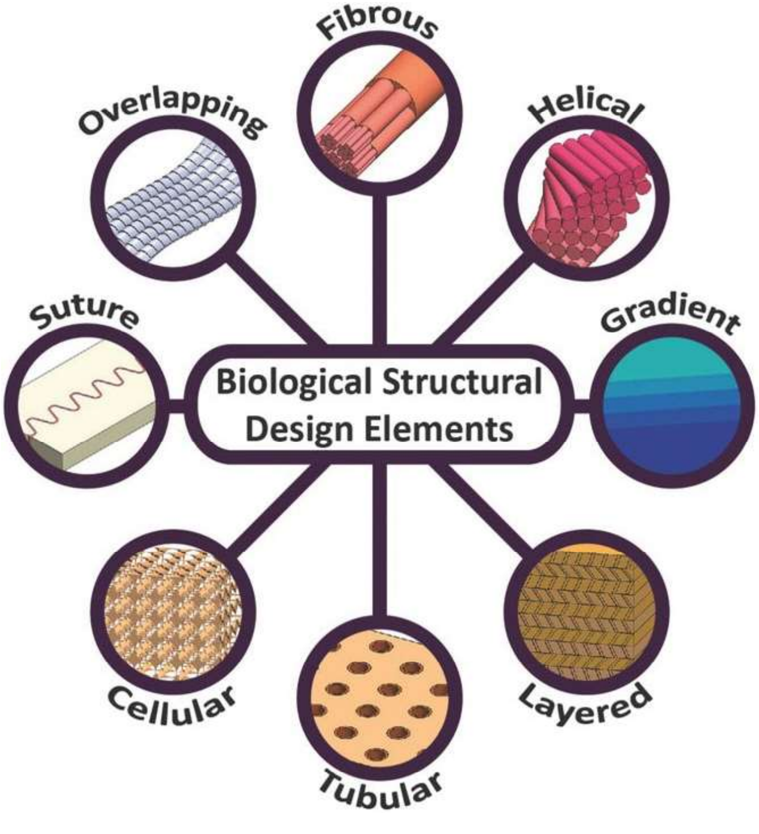


Figure 1. Diagram of the eight most common biological structural design elements [3]. [Used with permission from John Wiley and Sons]

In most instances, modifications to continuous fibre-reinforced composite materials fall broadly into categories that include, improving the interface of fibre-matrix components, introducing mechanisms to deflect, distribute, or dissipate stress to limit areas of high stress-concentrations, initiate tougher failure in a controlled manner to either defect or arrest the generated crack (introducing toughen response), or targeting the generally poor delamination strength (resin rich regions) between plies.

3. Current hierarchical composites designs and approaches

It is desirable to have fibres orientated in specified loading axis and to contain continuous fibres as these are more efficient with respect to mechanical loading [5]. Even with these design constraints, hierarchical approaches can be implemented to improve composite compression properties. A schematic of the composite designs discussed in the later sections are shown in Figure 2.

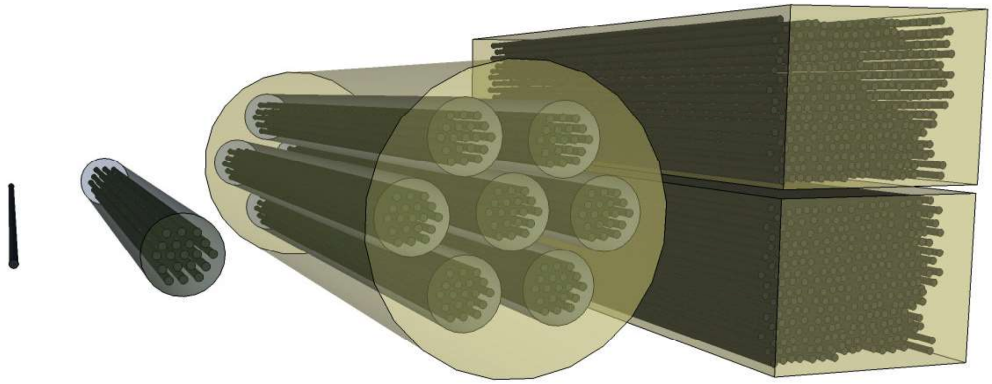


Figure 2. A schematic of the various length scales of the composite designs, from left to right, a single fibre (matrix omitted), a bundle of fibres in a matrix, a bundle-of-bundle composite, and a representation of a traditional unidirectional composite for comparison (shown with a gap to more clearly illustrate the plies).

3.1 Fibres

The shape and form of high performance (non-natural) fibres have usually been chosen for improved tensile properties and are uniform, continuous, circular, and small in diameter (~5-20 µm), but these characteristics may not be the optimal form for compressive loads. In Nature, the form of fibril scaffolds are normally non-circular, have defined periodicals of morphological changes, for instance bird feathers [6], and vary in diameter depending on their primary function. Another major difference between naturally occurring fibril/fibres and those artificially produced fibres are their hollow construction which allows for the transport of fluids throughout the organism, or to reduce weight for specific applications (e.g. flight); these features are not necessary for achieving ultimate mechanical performance using high performance constituents. Natural fibrils are often supported through a helical arrangement, or through a change in density of a porous or foam-like local structures (cellular and gradient). The complexity and refinement of the reinforcing elements of the structure changes from large features to smaller structures, which themselves can have specific alignment to aid support, when arranged about the parent fibril-structure. This alignment and change in length-scale is a key feature in improved lateral support exhibited by these materials. These laterally supporting architectures provide adequate dissipation and non-stress localising properties and are desirable for high performance systems in a bid to reduce the failure mode(s) associated with the onset of kink-band formations. The failure of composite materials in compression is often driven by poor lateral support and early formation of kink-bands as a result of the instabilities of the loads experienced by the primary reinforcing fibres. To mimic this lateral supporting motif, there have been multiple attempts to add nanoreinforcement to the fibre surface/interphase which has the added benefit of reducing stiffness mismatch between the fibre and the matrix [7]. Methods include directly synthesising/growing nanomaterials on the surface, or depositing pre-made nanomaterials by electrophoretic deposition or some other chemical grafting process; the simplest approach is to coat the fibres in a size containing dispersions of nanomaterials. All these approaches suffer from some limitations for instance difficulties in scaling production, or poor alignment of the nanomaterial. Alignment of the nanomaterials, on the parent structure, is of particular significance, and is one of the most challenging aspect of adding nanomaterials to mimic the arrangements observed in biological systems. It is expected that if the nanoreinforcement is aligned in the axis of the parent fibre there may be limited lateral support in the surrounding interphase. However, increases in surface areas from these processes improve the mechanical interlocking of the fibre with the surrounding matrix which can improve the interfacial/interphase properties. Altering the morphology of the fibres' cross-section (unduloid or cross section shape) is a less studied approach to create supporting motifs, with either commercial fibres acquired and further processed [8] or produced/synthesised in-house to create the desired forms [9]. Depending on the materials chosen (carbon, glass, etc.) synthesising non-circular cross-section fibres can have significant cost, equipment, and processing constraints. There is also interest in well aligned nanomaterial based fibres/veils, which satisfy the requirements for local alignment whilst containing strong, stiff, and tough reinforcement.

3.2 Matrix

The most commonly used and modified composite matrix is epoxy (thermoset) due to the ease of handling and manipulation at the laboratory scale. Whilst thermoplastics are generally tougher, they require high temperatures and pressures to form around fibres, and as such they have been studied less often. Additionally, thermoplastic moduli are low resulting in less support for the fibres in compressive loading conditions; this along with poor compatibility between the thermoplastic matrix and fibres leads to a reduced fibre-matrix interface and overall composite performance. Methods to improve epoxy toughness includes the introduction of rubber particles, and for improved stiffness the introduction of nanomaterials (typically carbon) [10]. Chemical functionalisation is frequently used to improve the dispersibility of nanomaterials in an epoxy matrix resin system. However, the addition of nanomaterials to the matrix, even if unagglomerated, can alter the processability, increasing viscosities, and leading to self-filtering of the nanomaterials by the parent fibres. In natural materials there is often localised reinforcement leading to a heterogeneous structure, yet in the majority of composite systems a homogenous reinforcement is preferred. Further investigations into the impact of localising adequately dispersed nanoreinforcement and their effect on failure modes [11] is an exciting area of investigation.

3.3 Bundle systems

Bundle systems are similar, but one order of magnitude greater in size than the fibres systems previously described. Analogous adaptations for bundle composites are consequently desired, with off-axis reinforcement sought. Bundle-like pultruded composite rods are commercially available, with high alignment, allowing research into the surrounding matrices to form bundle-of-bundles composites and hybridisations. Bundle composites bridge the reinforcement length scales between fundamental systems and the ply level.

3.4 Ply level systems

In natural layer structures, deformation and localised failures are promoted to limit damage progression into the whole system. To achieve the same effect in high performance materials, the alignment of fibres within a ply may be exploited to alter and manipulate the failure modes observed. At the ply level, the introduction of misalignment (to the loading direction) or confined reinforcement to an area can alter the composite properties drastically. Choosing specific arrangements that benefit the compressive properties of the system are a challenge, and it is likely that suppression of the kink-band formation through careful consideration of materials and layup will be a route to success.

4. Outlook

The approach of introducing hierarchical constructs to fibre-reinforced composites is not new, however, in the most challenging loading condition of compression, there are very limited studies. Taking a step back, the use of existing materials, processes, and architectures needs to be revised for their suitability for use in hierarchical composite for compressive loading conditions. Whilst the focus will remain on the constituents of the composite for improvements, the combinations and arrangement need to be investigated to truly establish their performance in compression. A collaboration between Imperial College London and the University of Bristol, along with industrial partners are taking on this challenge in a five-year UK Engineering and Physical Sciences Research Council (EPSRC) funded project. We hope to share our investigations and results shortly.

Acknowledgements

The authors kindly acknowledge the funding for this research provided by UK Engineering and Physical Sciences Research Council (EPSRC) programme Grant EP/T011653/1, Next Generation Fibre-Reinforced Composites: a Full Scale Redesign for Compression a collaboration between Imperial College London and the University of Bristol.

5. References

1. Lakes R. Materials with Structural Hierarchy, Nature, 1993; 361:511-515, DOI: 10.1038/361511a0.
2. Bruck HA, Evans JJ, Peterson ML. The Role of Mechanics in Biological and Biologically Inspired Materials. Experimental Mechanic 2002; 42:361–371, DOI: 10.1007/BF02412140.
3. Naleway SE, Porter MM, McKittrick J, Meyers MA. Structural Design Elements in Biological Materials: Application to Bioinspiration. Advanced Materials 2015; 27:5455-5476, DOI: 10.1002/adma.201502403.

4. Masselter T, Hesse L, Böhm H, Gruhl A, Schwager H, Leupold J, Gude M, Milwich M, Neinhuis C, Speck T. Biomimetic optimisation of branched fibre-reinforced composites in engineering by detailed analyses of biological concept generators. Bioinspiration & Biomimetics 2016; 11:5:055005, DOI: 10.1088/1748-3190/11/5/055005.
5. Halpin JC, Kardos JL. Strength of Discontinuous Reinforced Composites: I. Fiber reinforced composites. Polymer Engineering and Science 1978; 18:6:496-504, DOI: 10.1002/pen.760180612.
6. Lingham-Soliar T, Bonser RHC, Wesley-Smith J. Selective biodegradation of keratin matrix in feather rachis reveals classic bioengineering. Proceedings of the Royal Society B 2010; 277:1161-1168, DOI: 10.1098/rspb.2009.1980.
7. Khan SU, Kim JK. Impact and Delamination Failure of Multiscale Carbon Nanotube-Fiber Reinforced Polymer Composites: A Review. International Journal of Aeronautical and Space Science 2011; 12:2:115-133, DOI: 10.5139/IJASS.2011.12.2.115.
8. Rodricks CW, Greenfeld I, Wagner HD. Polymer beads as interfacial obstacles in fibre composites. Composite Science and Technology 2021; 210:108793, DOI: 10.1016/j.compscitech.2021.108793.
9. Lee YS, Basova YV, Edie DD, Reid LK, Newcombe SR, Ryu S.K. Preparation and characterization of trilobal activated carbon fibers. Carbon 2003; 41:13:2573-2584, DOI: 10.1016/S0008-6223(03)00376-2.
10. Kinloch IA, Suhr J, Lou J, Young RJ, Ajyan PM. Composites with carbon nanotubes and graphene: An outlook. Science 2018; 362:6414:547-553, DOI: 10.1126/science.aat7439.
11. Abidin MSZ, Herceg TM, Greenhalgh ES, Shaffer MSP, Bismarck A. Enhanced fracture toughness of hierarchical carbon nanotube reinforced carbon fibre epoxy composites with engineered matrix microstructure. Composites Science and Technology 2019; 170:85-92, DOI: 10.1016/j.compscitech.2018.11.017.