Damage Tolerance and Durability of Structural Power Composites

Award nos.: FA9550-17-1-0338, FA9550-17-1-0244, FA9550-17-1-0251

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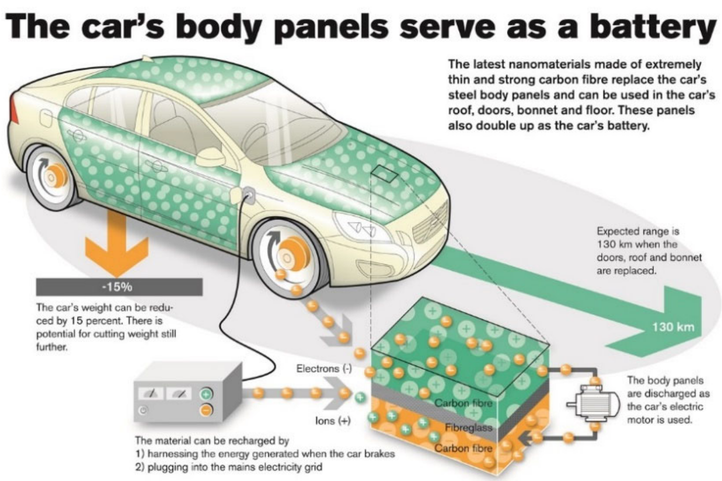
CHALMERS

KTH VETENSKAP OCH KONST

Imperial College London

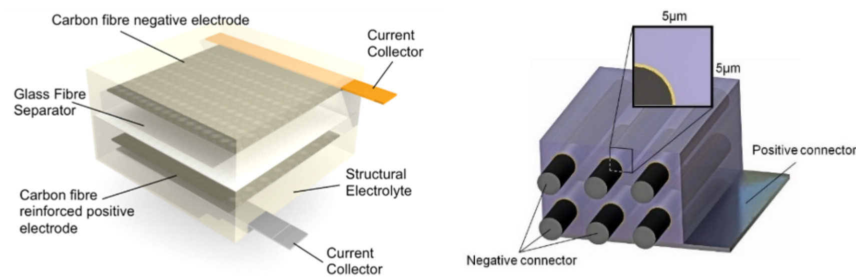
Structural Power Composites – ‘Massless’ Energy

- Structural composites imbued with capacity to store/deliver electrical energy;
- Profoundly disruptive approach to using structural materials;
- We have pioneered this concept, and recognised as the world leaders in this emerging technology.

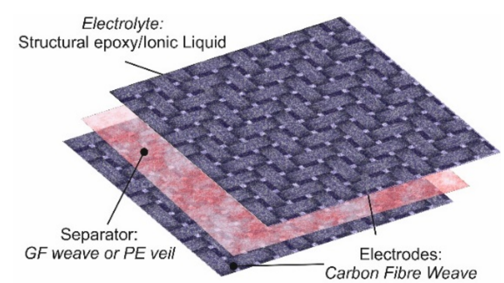


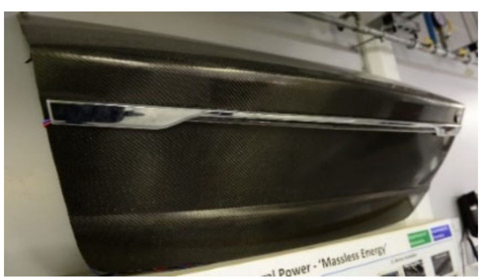
New York Times

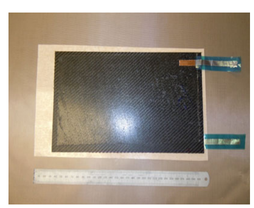
Structural Batteries



Structural Supercapacitor





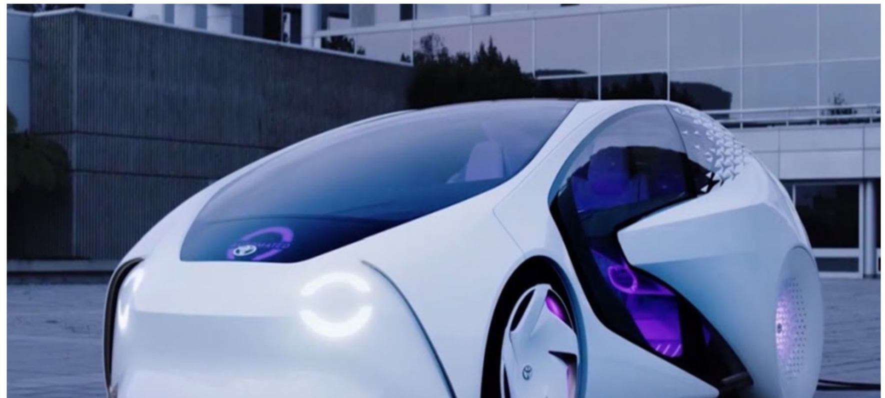


Single cell

Multifunctional bootlid demonstrator for Volvo S80

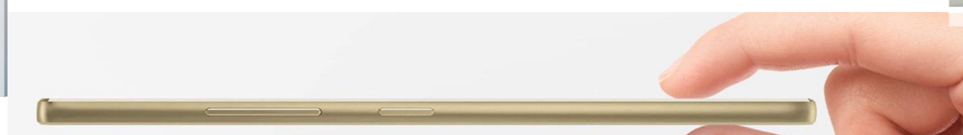
Vision for Structural Power

Slender wings →
reduced drag & thus greater range



Huge mass and volume reductions →
Sustainable transportation

New places to store energy →
Multifunctional infrastructure



'Slenderisation' → ***phones as thin as credit cards***

Localisation of power →
reduced wiring

Imbued functionality →
'batteryless' devices

Multifunctional structural materials → ***innovative engineering & design freedom***

Imperial Structural Power Team

Dr David Anthony
Reinforcements

Prof Shaffer

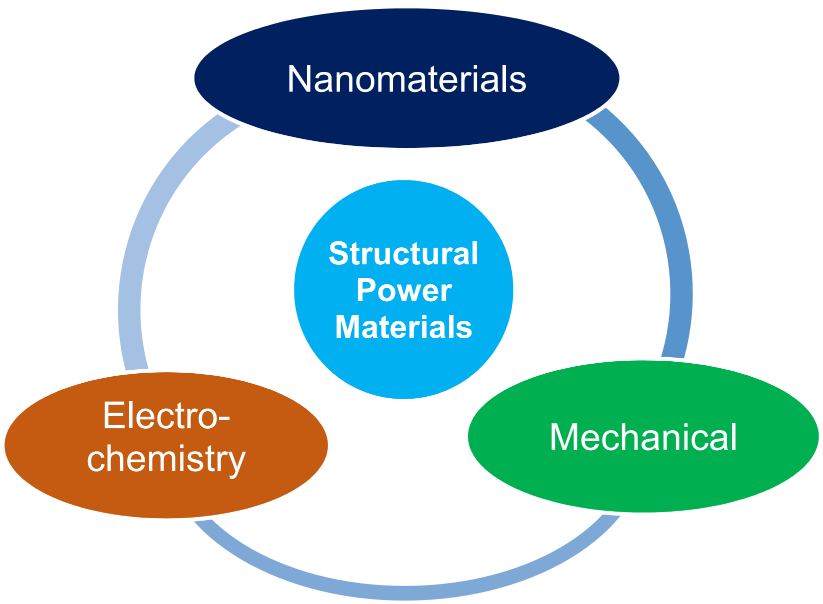
Dr Seyedalireza Razavi
Current Collection

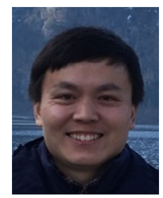
Chanhui Lee
Topology optimisation

Maria Valkova
Multifunctional modelling

Kalpana Balaskandan
Non-laminated devices

Dr Evgeny Senokos
Nanomaterials





Dr Guocheng Qi
Device Manufacture

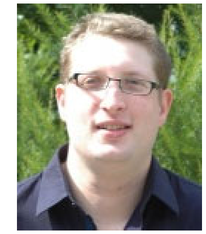
Dr Sang Nguyen
Multifunctional design

Dr Francesca Pernice
Mechanical Characterisation

Prof Kucernak

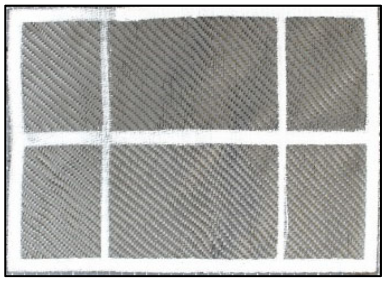
Prof Greenhalgh

Development of CF/CAG reinforcement/electrodes and strategies to introduced curvature

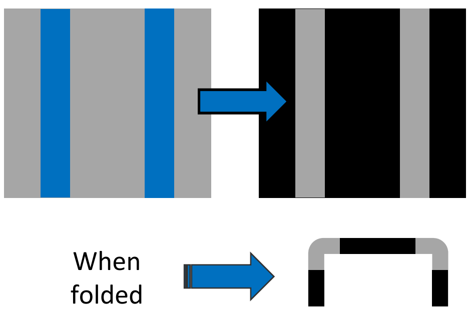


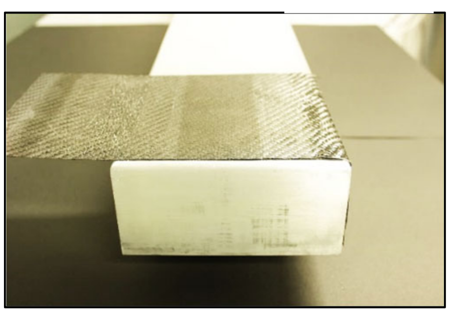
David
Reinforcements

PLA mask



Polylactic acid (PLA) mask





Forming of CAG/CF lamina around tool

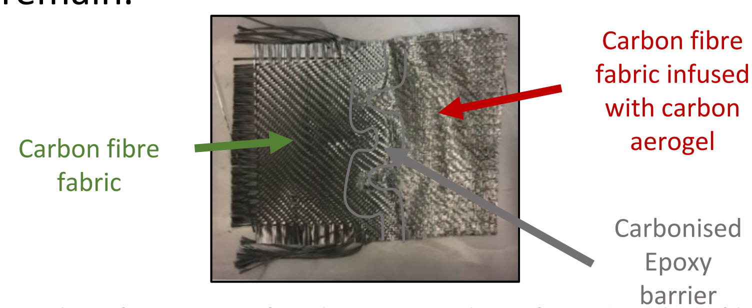
Objective:
How can improve the CAG/pyrolysis process to minimise the damage to the carbon fibres and permit fabrication of curved structures?

Method:
The strategy has been to introduce 'fold-lines' in the lamina prior to CAG precursor infusion. This permits regions of high local curvature to be introduced.

Methods of improving the CAG have including lowering the pyrolysis temperatures and introduce nanocarbons to enhance the toughness.

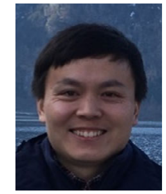
Achievements:
Successfully demonstrated two methods; epoxy borders and PLA masks, to facilitate curvature of the CAG/CF lamina.

GO and CNTs introduced into the CAG, but fabrication challenges associated with self-filtration remain.



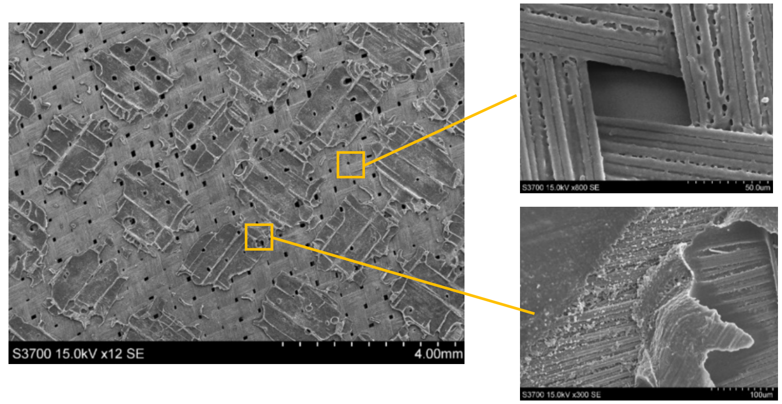
Nguyen, S., et. al., Mechanical and physical performance of carbon aerogel reinforced carbon fibre hierarchical composites, Composites Science and Technology 182, (2019).

Manufacturing studies



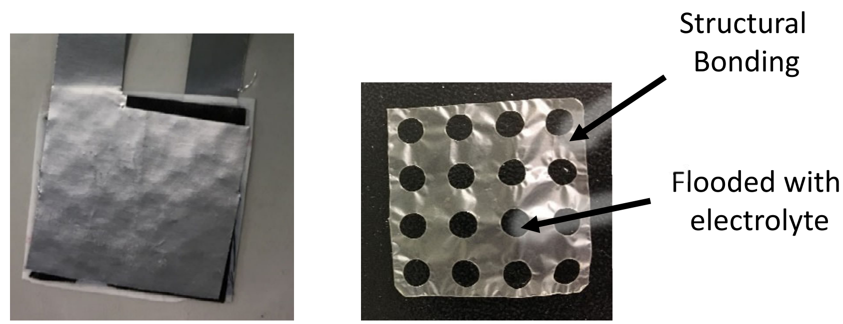
Dr Guocheng Qi
Device Manufacture

Objective:
What is the best device assembly strategy to achieve good delamination resistance and permit good ionic conduction?



Method:
Development of multifunctional matrix has led to difficulties with controlling the heterogeneity of the microstructure when introduced to the fibres.

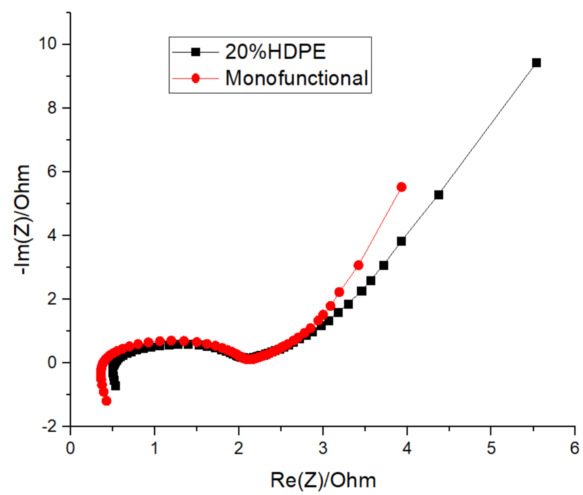
An alternative (pragmatic) approach taken, by sandwiching a porous TP film between electrodes.



Achievements:
Successfully identified suitable TP (HDPE) & demonstrated 20% film coverage provides a reasonable balance between delamination resistance and ionic conductivity.

Modelling studies underway to identify optimum configuration (i.e. pore size, areal fraction and shape)

Detailed characterization and scale-up studies now underway.

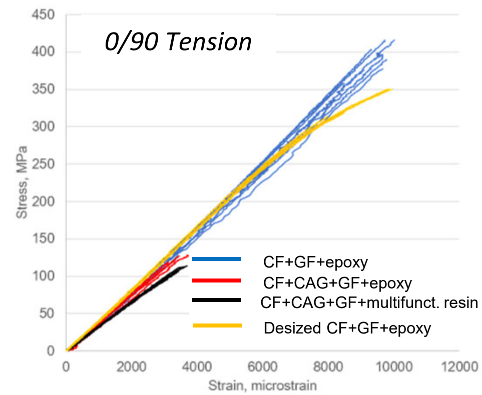


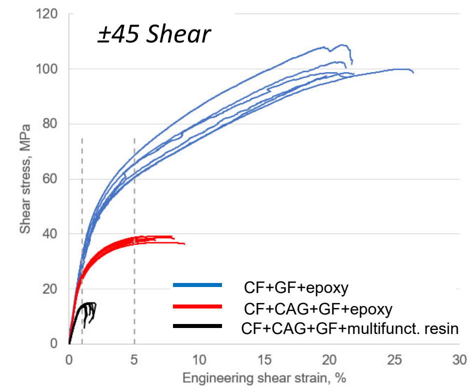
Mechanical characterisation….

Dr Francesca Pernice
Mechanical Characterisation

Objective:
Develop simultaneous electrochemical and mechanical testing methodologies (including delamination resistance), for conventional and spread tow device testing.

Method:
Mechanical characterisation (uniaxial tension and in-plane shear) of mono and multifunctional devices, with detailed characterisation of the micromechanisms.

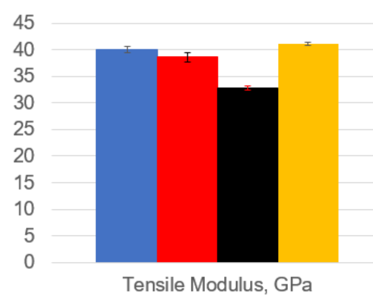


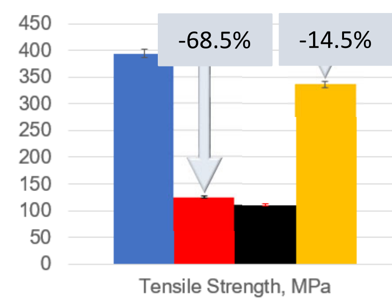


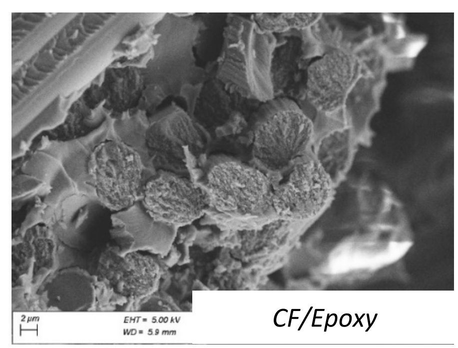
Achievements:
CAG infusion into the CF fabric caused a reduction in tensile strength, while tensile modulus was unchanged.

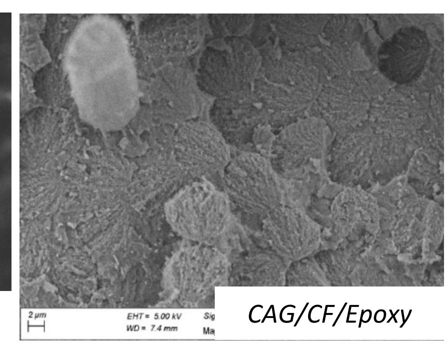
Strength reduction associated with chemistry of the CAG synthesis and not the thermal history.

In-plane shear properties dictated by the electrode/separator interface and ultimately by the amount of multifunctional resin at the interface, which bonds well to the fibres.



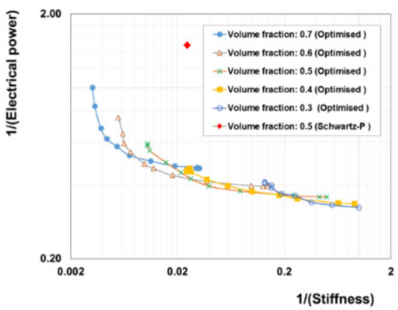


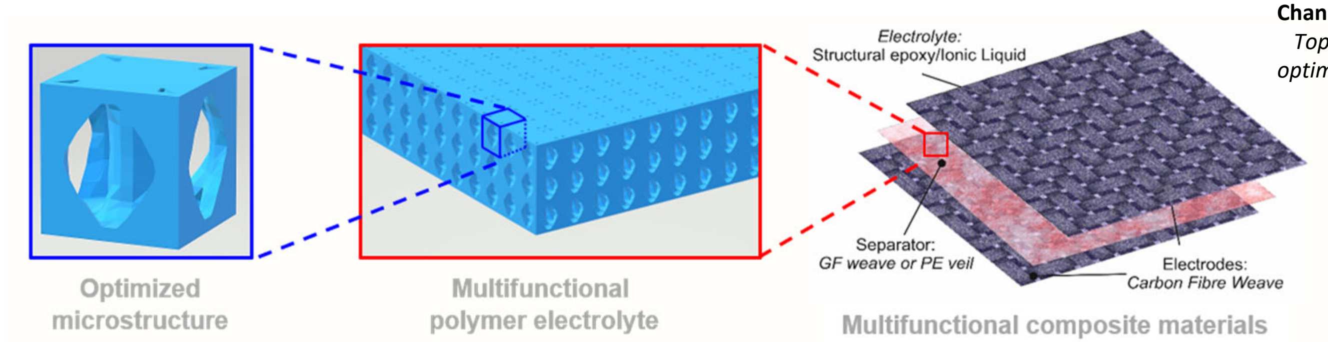




Material Optimisation….

Chanhui Lee
Topology optimisation



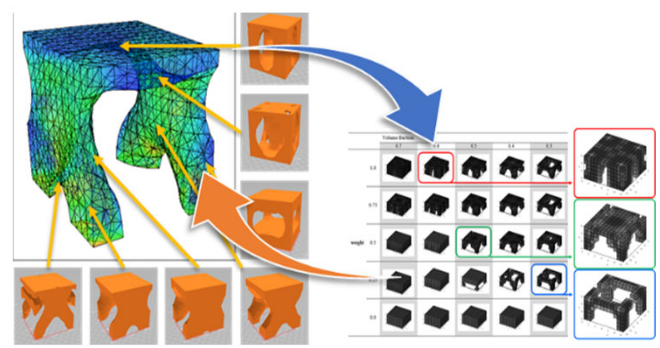


Objective:
Define matrix microstructures which maximises both mechanical & electrochemical performance?

Method:
Employed topology optimization for microstructural modelling for different mechanical/electrochemical weightings, considering different volume fractions of epoxy phase. Validated predictions against 3D printed microstructural unit cells.

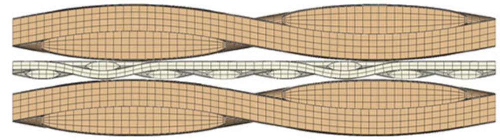
Achievements:
Demonstrated optimized configurations for tension and shear loadings, and validated against 3D printed configurations.

Extended strategy to multiscale optimization, using a library of optimized cells to optimize larger unit cells.



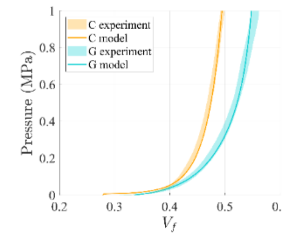
Lee, C., Greenhalgh, E.S., Shaffer, M.S.P., Panesar, A., Optimized microstructures for multifunctional structural electrolytes, Multifunctional Materials 2(4), (2019).

Multiphysics modelling of devices



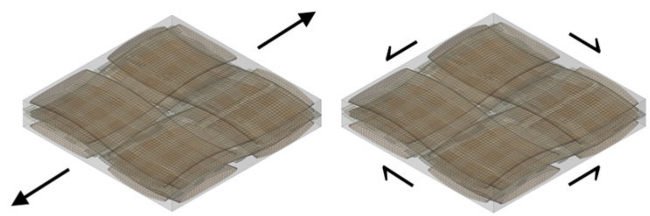
Maria
Multifunctional modelling

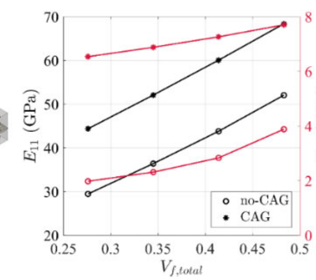
Objective:
Develop predictive models for mechanical and electrochemical performance, which can be used for device optimisation.



Method:
Initial focus has been on consolidation modelling of the laminate during fabrication using FEA. This defines the subsequent device microstructure.

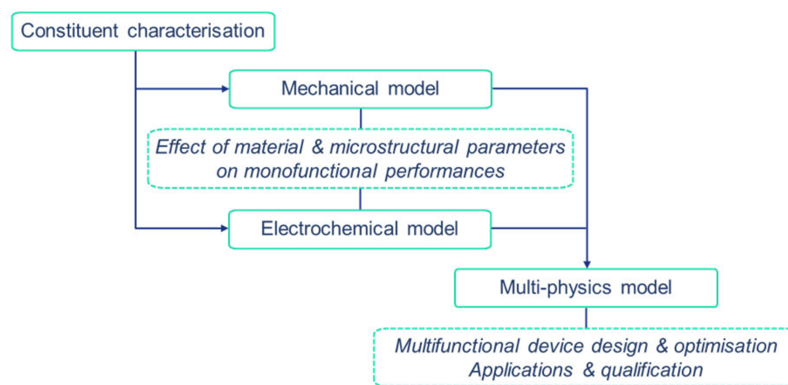
Following this mechanical and electrochemical models are under development, culminating in a coupled predictive tool.





Achievements:
Consolidation modelling completed, resulting in a tool to predict the reinforcement microstructure.

Mechanical models underway, predicting the influence of CAG on the elastic response of the device. Electrochemical models are currently under development.



Valkova, M., Greenhalgh, E.S., Shaffer, M.S.P., Kucernak, A., Predicting the compaction of hybrid multilayer woven composite reinforcement stacks, Composites Science and Technology 133(105851), (2020).

Multifunctional Design and Demonstration

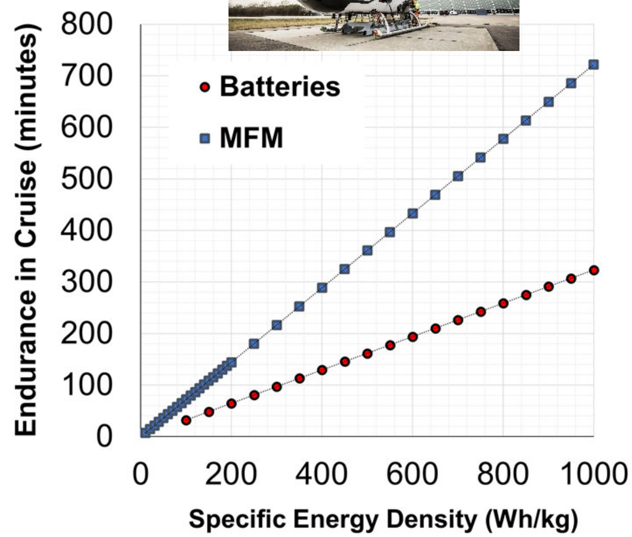
Sang
Multifunctional design

Objective:
How do we design multifunctional platforms, and compare their performance to that of the conventional equivalent systems?

Method:
Design methodologies have been under development, and applied to various platforms including air-taxi, fully electric airliner, aircraft cabin and boat.

Detailed study of multifunctional aircraft floor panels to power personal display units.

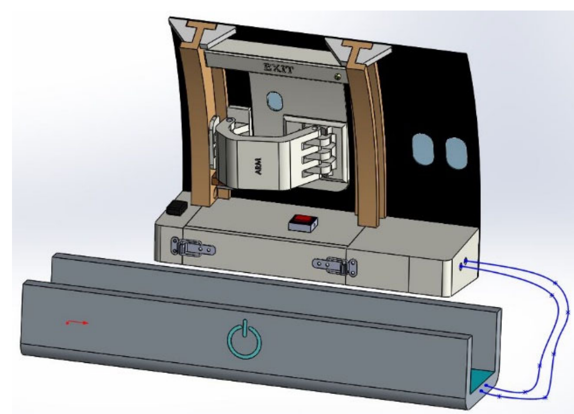
Currently assembling a multifunctional demonstrator which will open/close an scale down aircraft door.



Achievements:
Demonstrated (for Cityairbus) for a given energy density, structural batteries will provide over double the range of the vehicle compared to that powered by conventional batteries.

Demonstrated feasibility of using structural power in the aircraft cabin.

Multifunctional demonstrator currently being assembled, for delivery in December 2020.



S. N. Nguyen, et. al. Structural Power Performance Requirements for Future Aircraft Integration, ICCM22, Melbourne, Australia, 11-16 August 2019.

Project Team KTH

- PI: Dan Zenkert
- Co-PI: Mats Johansson
- Ph.D.-students:

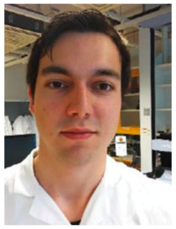
Dan Zenkert
PI

Mats Johansson
Co-PI

Göran Lindbergh
Professor Electrochemistry

Lynn Schneider
Ph.D.-student

Wilhelm Johannisson
Ph.D.-student



Karl Bouton
Ph.D.-student

Ross Harnden
Ph.D.-student

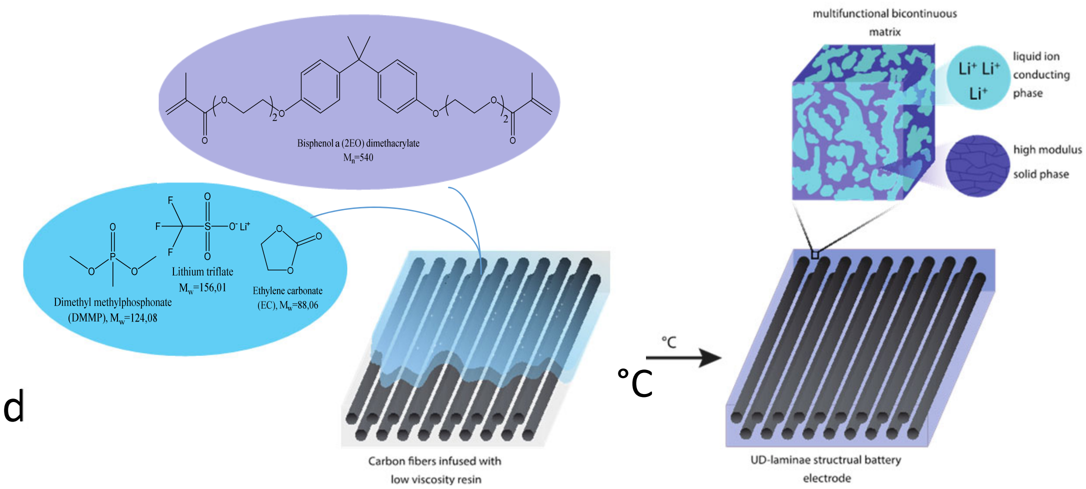
Kevin Peuvot
Ph.D.-student

Yasemin Duygu Yucel
Ph.D.-student

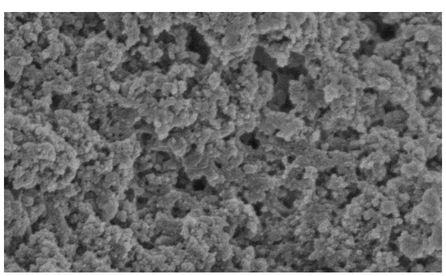
Bicontinuous electrolytes via thermally initiated polymerization for structural lithium ion batteries

Objective:
Make a multifunctional composite matrix materials that can transfer load and conduct ions for structural batteries.

Method:
Reaction induced phase separation creates a two-phase structural battery electrolyte with one stiff load carrying polymer network and a percolating liquid electrolyte for ion conduction.



Monomer ◐ non-polar   Electrolyte ● polar



Achievements:

Combined with carbon fibres to make a structural battery half-cell

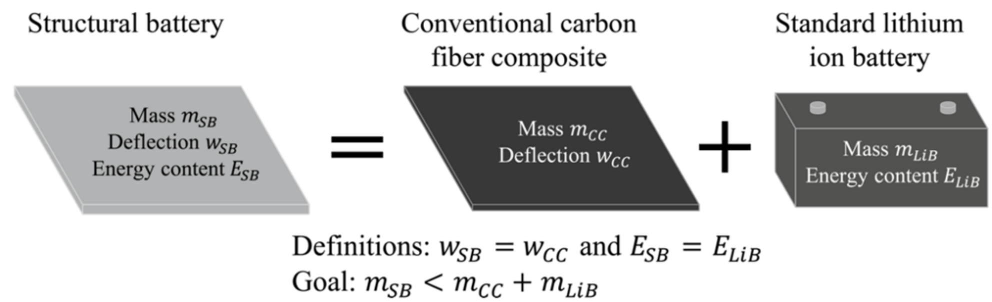
Thermally cured at 80^{o}C

Electrochemical capacity: around 200 mA/g

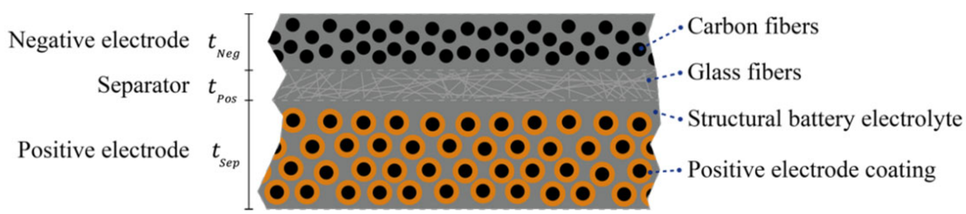
Transverse Young’s modulus: 1.3 GPa

Schneider L, Ihrner N, Zenkert D. Johansson M., "Bicontinuous electrolytes via thermally initiated polymerization for structural lithium ion batteries", *ACS Applied Energy Materials*, Vol 2 (6), 2019, pp 4362-4369

Model of a structural battery and its potential for system level mass savings

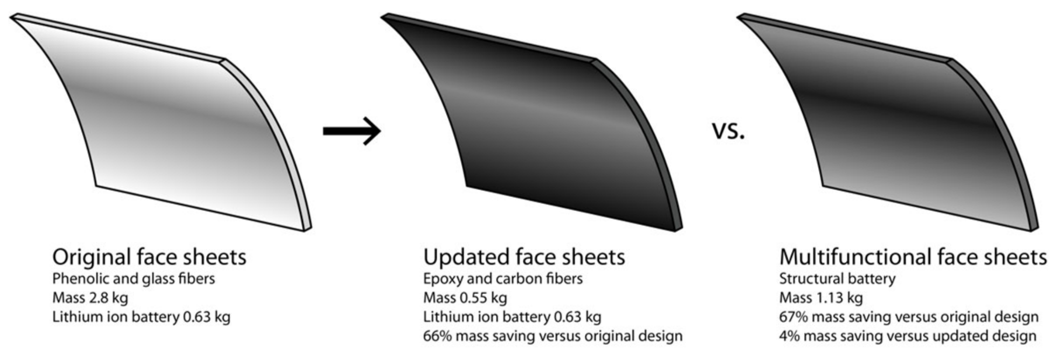


Objective:
Can multifunctional structural batteries save mass compared to state-of-the-art monofunctional systems?



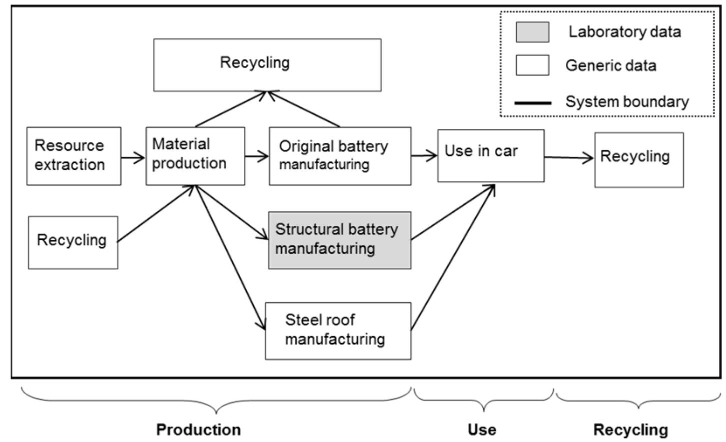
Method:
Model electrochemical and mechanical properties of a structural battery laminate as function of constituent properties. Compare mass with monofunctional systems with equivalent properties.

Achievements:
The potential mass savings for an aircraft interior part of current glass fibre design could be as high as 67%.



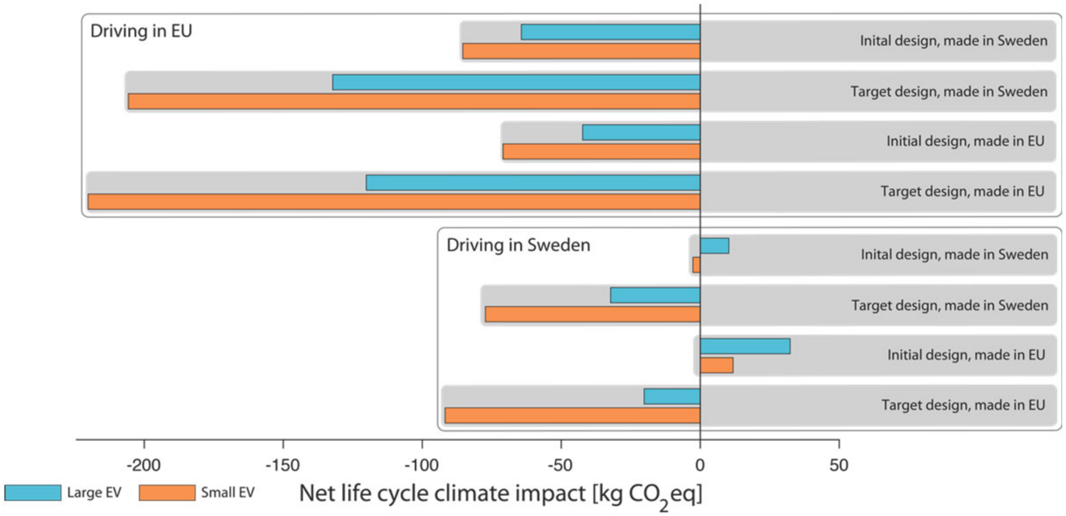
Johannisson W., Zenkert D, Lindbergh G., ”Model of a structural battery and its potential for system level mass savings”, *Multifunctional Materials*, Vol 2, 035002, 2019

Prospective life cycle assessment of a structural battery



Objective:
What is the environmental impact of structural batteries compared to monofunctional materials and systems over a life-time use?

Method:
Cradle-to-grave LCA analysis of structural battery component compared with monofunctional structure and traction battery.



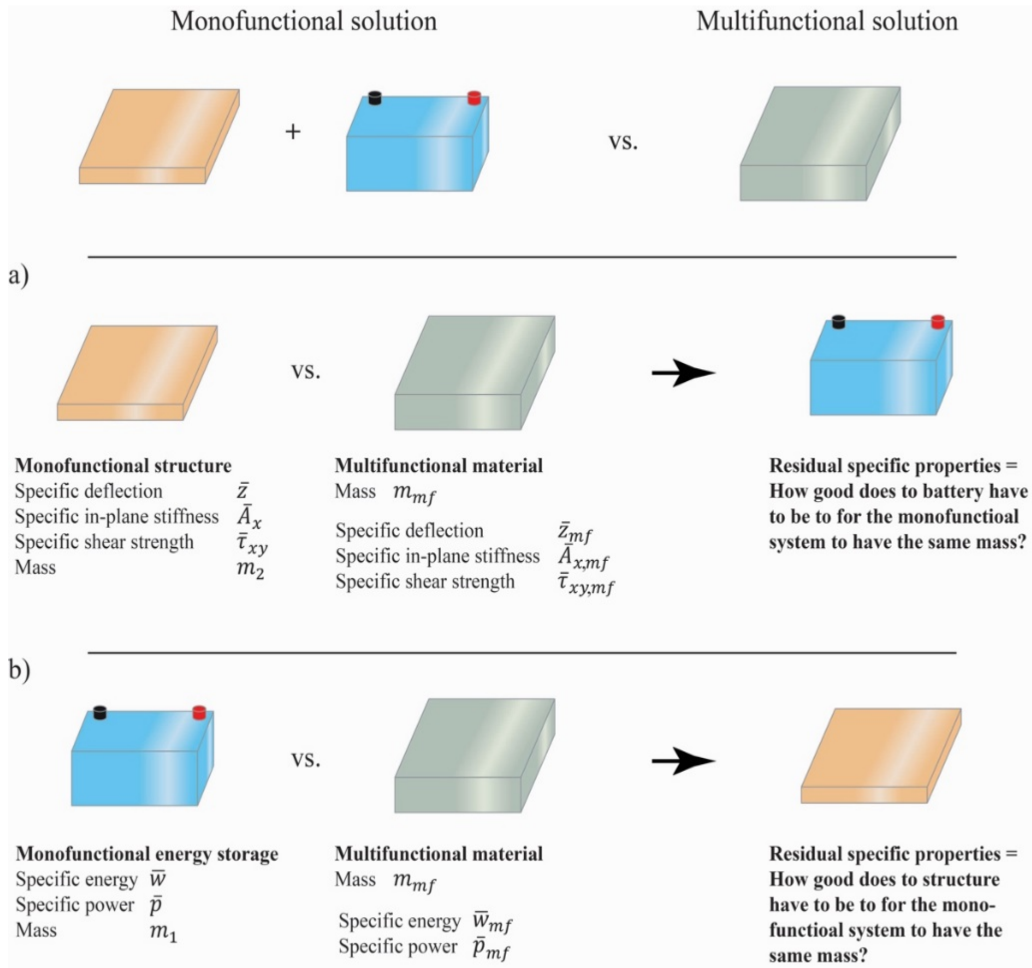
Achievements:
Net life cycle climate impacts examined with a structural battery roof instead of a steel roof in a EV For all the cases with European electricity mix the structural battery roof reduces climate impact.

Zackrisson M., Jönsson C., Johanisson W., Fransson K., Posner S., Zenkert D., Lindbergh G., "Prospective life cycle assessment of a structural battery", *Sustainability*, Vol 11, 5679, 2019

A residual performance methodology to evaluate multifunctional systems

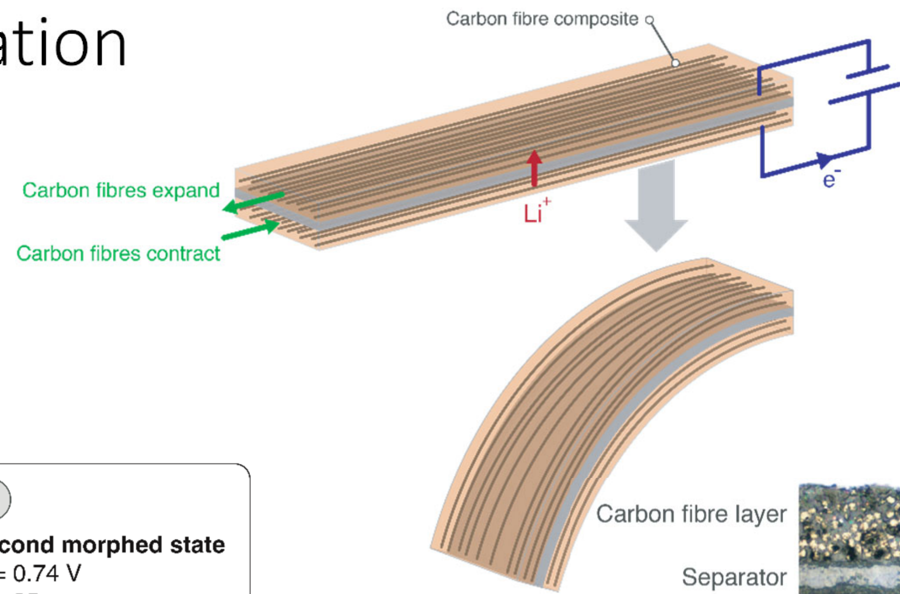
Objective:
Find a new multifunctional metric to more pedagogically quantify the benefit of multifunctional materials

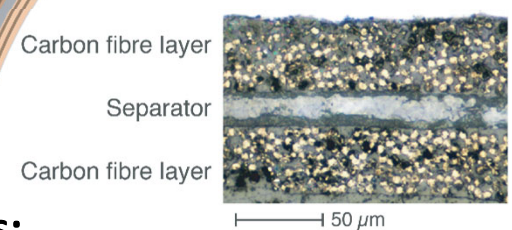
Method:
Introducing residual specific properties required for a monofunctional system to have the same mass as a multifunctional system.



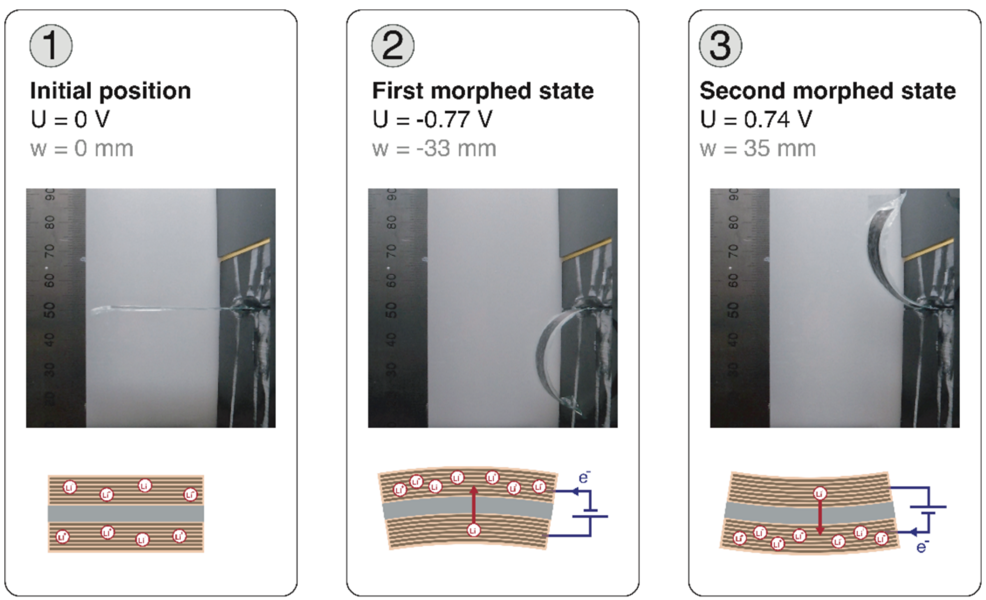
Johannisson W., Nguyen S., Lindbergh G., Zenkert D., Greenhalgh E., Shaffer M., Kucernak A., ”A residual performance methodology to evaluate multifunctional systems”, Multifunctional Materials, Vol 3(2), 2020, 025002

Shape-morphing carbon fiber composite using electrochemical actuation





Objective:
Make a carbon fibre composite that changes shape using ion-insertion similar to charge/discharge cycles in a Li-ion battery.



Achievements:
- Large displacements possible
- Inherent zero-power hold
- Low actuation voltages (1.5V)
- High stiffness and low density
- Limited rate at present

https://movie-usa.glencoesoftware.com/video/10.1073/pnas.1921132117/video-1

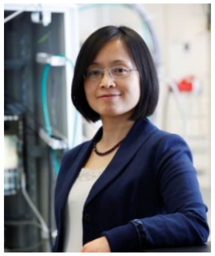
Johannisson W., Harnden R., Zenkert D., Lindbergh G., "Shape-morphing carbon fibre composite using electrochemical actuation", *Proceedings of the National Academy of Sciences*, Vol 117(14), 2020, https://doi.org/10.1073/pnas.1921132117

Project Team Chalmers

- PI: Leif Asp
- Co-PIs: Fang Liu and Ralf Jänicke
- Post-doc: Johanna Xu
- Ph.D.-students: David Carlstedt, Shanghong Duan and Vinh Tu

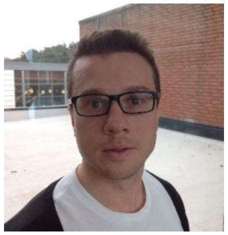
Prof Leif Asp

Dr Ralf Jänicke



Dr Fang Liu

Dr Johanna Xu
Material characterisation & modelling

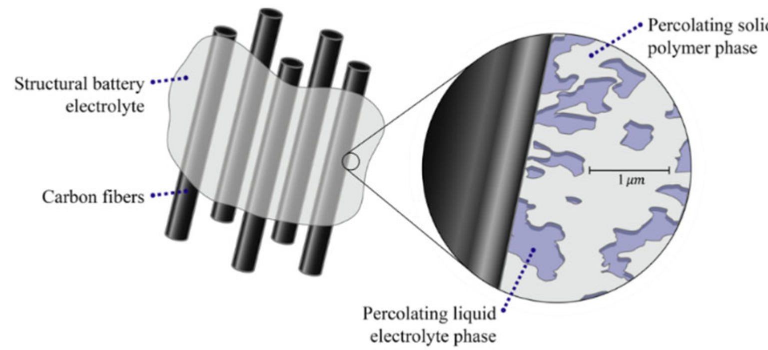


David Carlstedt
Modelling and characterisation

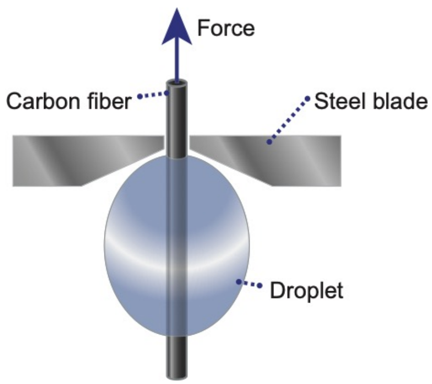
Vinh Tu
SBE *Modelling*

Shanghong Duan
Material analysis

Characterization of the adhesive properties between structural battery electrolytes and carbon fiber

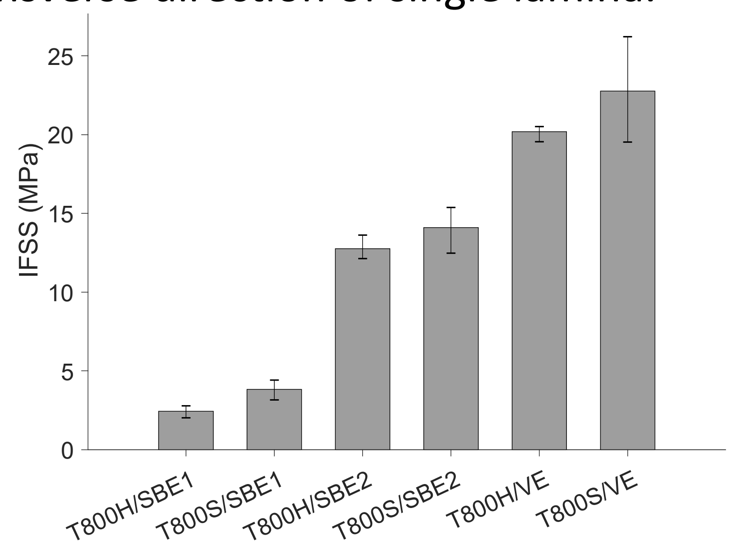


Objective:
What is the interfacial strength between carbon fibres and the structural battery electrolyte?



Method:
Measured using both single droplet tests and bending tests in the fibre transverse direction of single lamina.

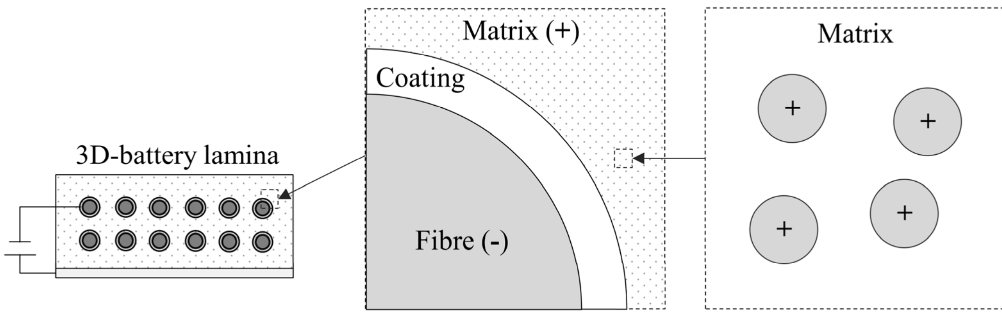
Achievements:
Interfacial strength depends more on the composition of SBE than on carbon fibres used. Slightly lower interfacial strength than for a homogenous polymer matrix. -→Promising properties for realisation of structural batteries.



Xu J., Johannisson W., Johansen M., Liu F., Zenkert D., Asp L., Lindbergh G., "Characterisation of the adhesive properties between structural battery electrolytes and carbon fibres", *Composites Science and Technology,* Vol 188, 2020, 107962

Effects of state of charge on elastic properties of 3D structural battery composites

Objective:
What are the effects of state of charge (SOC) on the elastic properties of a structural battery composite?



Method:
Perform a parametric study of the effects on elastic properties with a change in SOC.

Achievements:
A semi-analytical model to analyse the mechanical properties of 3D structural battery composites has been developed and verified.

From parametric studies the transverse elastic properties E_2 and G_{23} and the in-plane shear modulus G_{12} are found to be highly affected by the SOC for critical configurations.

Carlstedt D, Marklund E, Asp LE. Effects of state of charge on elastic properties of 3D structural battery composites. *Composites Science and Technology*. Vol 169, 2019, pp 26-33.

Thermal and diffusion induced stresses in a structural battery under galvanostatic cycling

Objective: What are the implications of the generated heat and expansion / shrinkage of the constituents on the internal stress state and mechanical properties of structural battery composites?

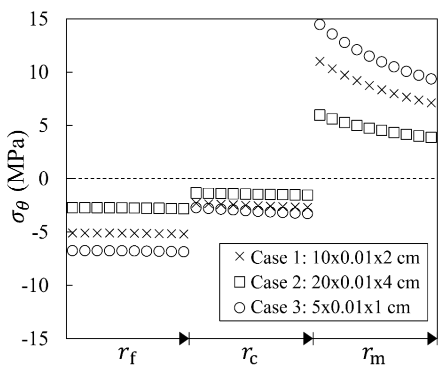
Method: Perform thermo-mechanical analyses considering diffusion (ion-currents) and resistive heating (electron-currents) in the structural electrolyte and carbon fibres, respectively

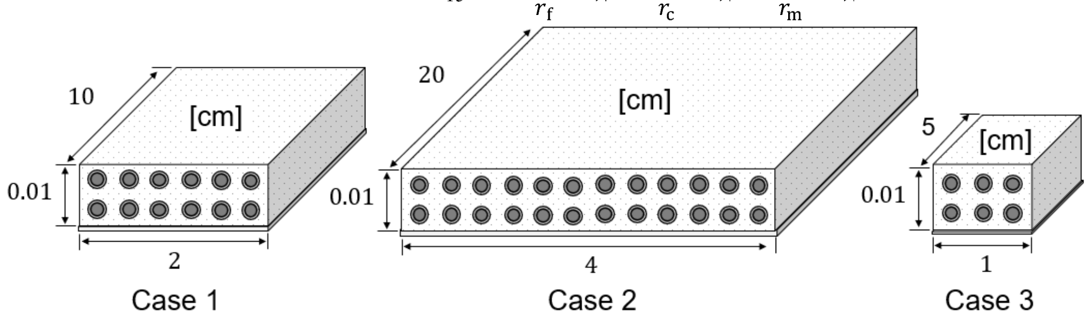
C-rate = 1

Case 1 (medium): $\Delta T = 9.8$ °C

Case 2 (large): $\Delta T = 35$ °C

Case 3 (small): $\Delta T = 3.4$ °C





Achievements:

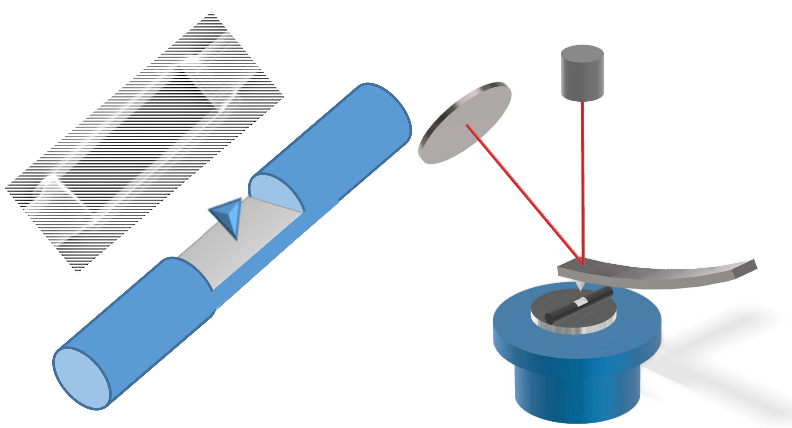
Generated heat strongly affects the internal stress state in structural battery composites

The charge / discharge current, lamina dimensions and residual stresses have significant effect on the internal stress state and effective properties of the composite lamina.

Carlstedt D, Asp LE. Thermal and diffusion induced stresses in a structural battery under galvanostatic cycling. *Composites Science and Technology*. 179, 2019, pp. 69-78.

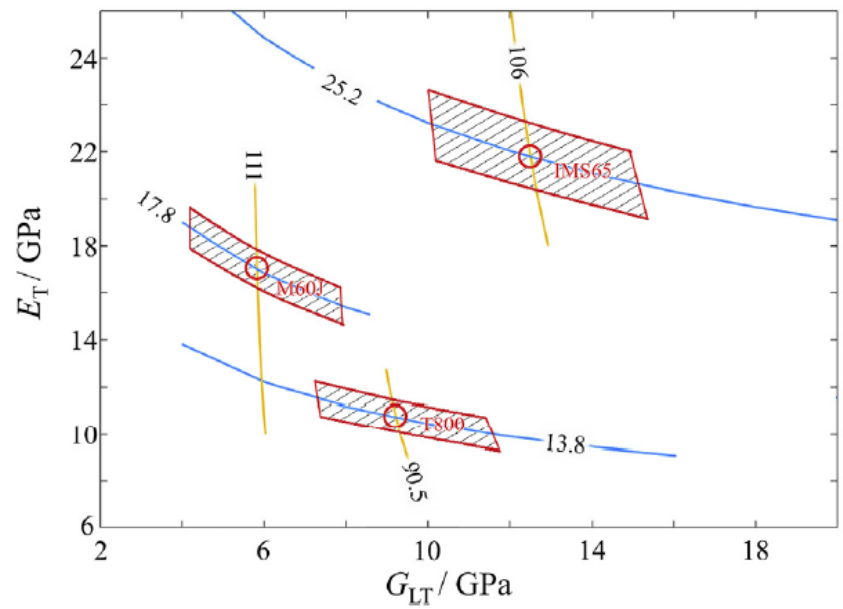
Determination of transverse and shear moduli of single carbon fibres

Objective: Determine the longitudinal, transverse and shear moduli of individual carbon fibres.



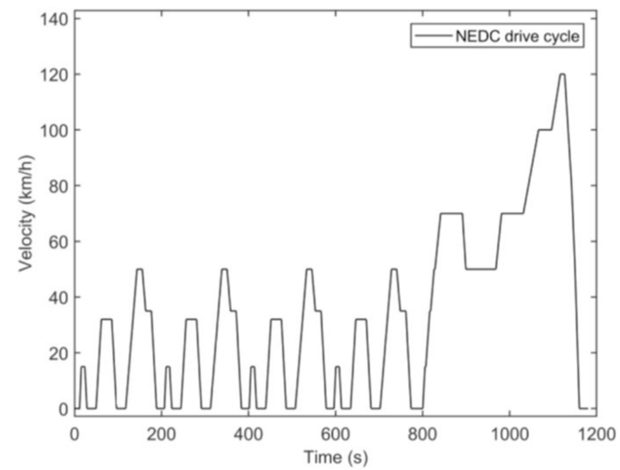
Method: Use FIB/SEM to produce flat surfaces for indentation tests using AFM.

Achievements: E_l, E_t, G_{lt} determined for T800, IMS65 and M60J fibres.



Duan S, Liu F, Pettersson T, Creighton C, Asp LE. Determination of transverse and shear moduli of single carbon fibres. *Carbon*. Vol 158C, 2020, pp 772-782.

Performance analysis framework for structural battery composites in electric vehicles



Objective: Develop a novel modelling framework to estimate system level performance of EVs using a structural battery composite material.

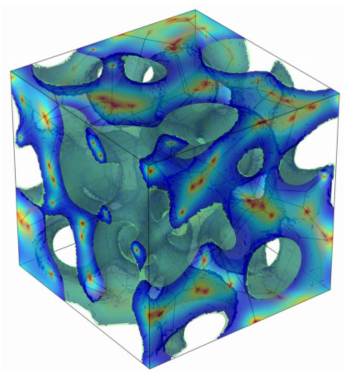
Method: Electrical and mechanical properties are derived from material data of the constituents, device design and connection / layup schemes.

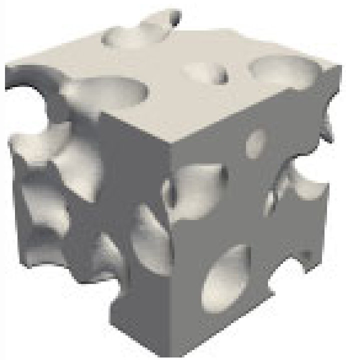
Achievements: Knowledge of the multifunctional, i.e. electrical and mechanical, performance of the structural battery composite allows for estimation of drive range for any known drive cycle.

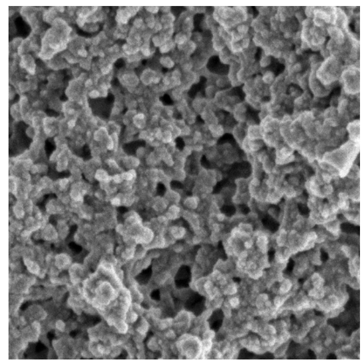
Carlstedt D, Asp LE. Performance analysis framework for structural battery composites in electric vehicles. *Composites Part B*, Vol.186, 2020, p 107822.

Performance of Bicontinuous Structural Electrolytes

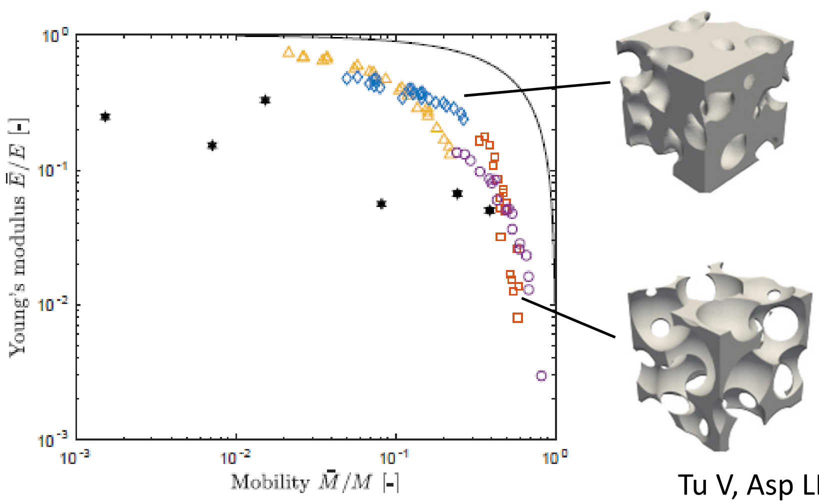
Objective: Develop a computational method to identify highly multifunctional SBE architectures.







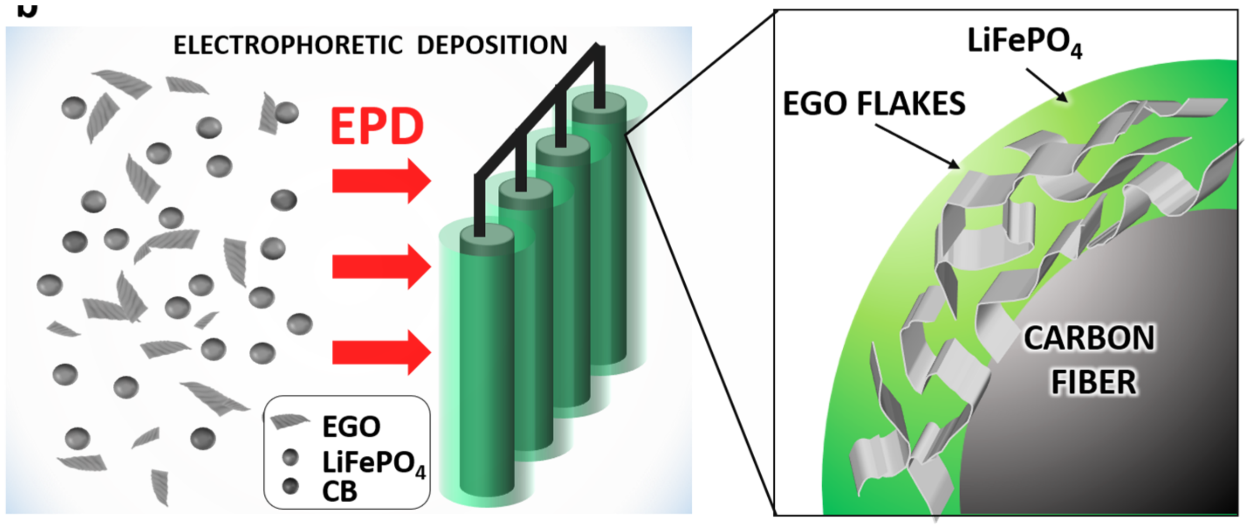
Method: The investigated microstructural topologies are realizable over wide porosity ranges yet forming a bicontinuous system.



Achievements:
The computational method provides a cheap, fast and reliable way to guide polymer synthesis of bicontinuous SBEs.

Tu V, Asp LE, Shirshova N, Larsson F, Runesson K, Jänicke R. Performance of Bicontinuous Structural Electrolytes. *Multifunctional Materials*, **3**, 2020, 025001.

Electrophoretic coating of LiFePO4/Graphene oxide on Carbon Fibers as High-Performance Cathode Electrodes for Structural Lithium Ion Batteries



Objective: To develop a binder-free method to deposit a composite of $LiFePO_4$ and electrochemically exfoliated graphene oxide (EGO) on CF.

Method: We use Electrophoretic Deposition as a versatile, scalable and cost-effective technique to deposit uniform coatings on substrates with complex shapes

Achievements: Tests performed on full cells with pristine CF as anode demonstrate:

Specific energy density of 168.8 $Wh.kg^{-1}$

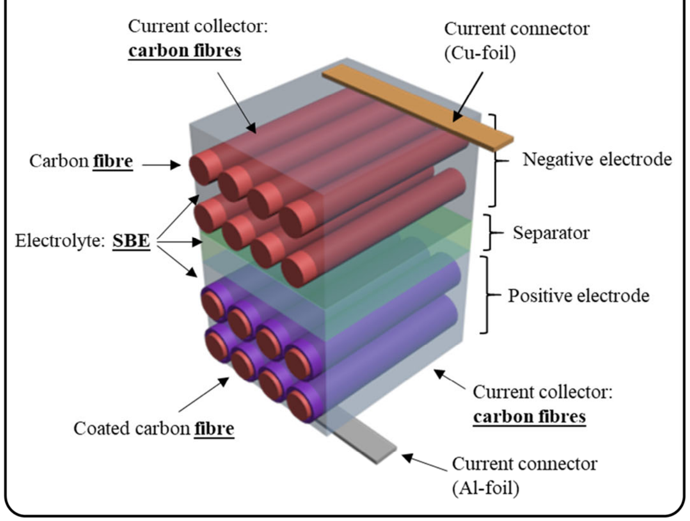
Power density of 1.5 $kW.kg^{-1}$

80% capacity retention at 1 C over 300 cycles.

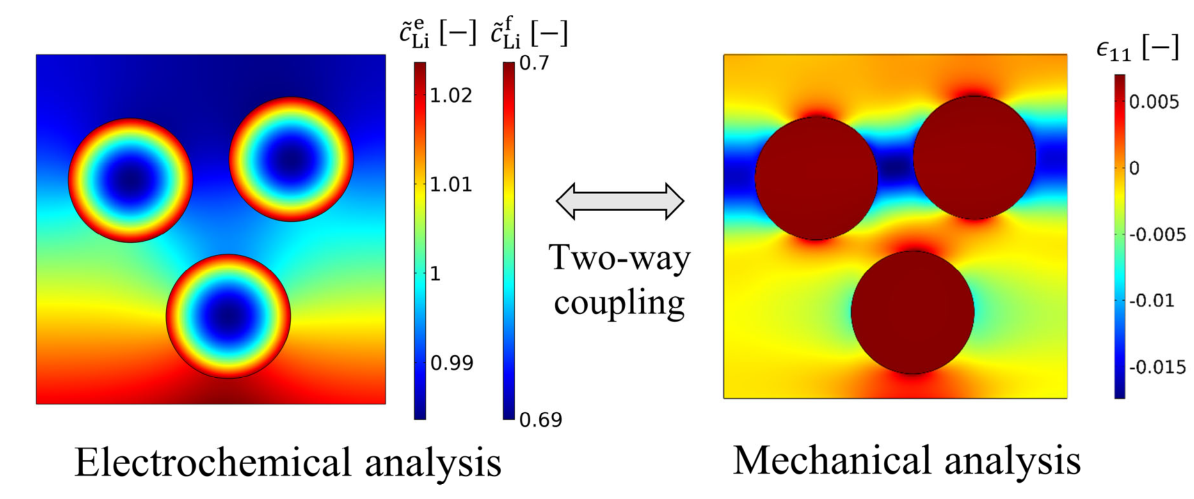
Sanchez JS, et al. Submitted, 2020.

Electro-chemo-mechanically coupled computational modelling of structural batteries

Structural battery design



Electro-chemo-mechanical framework



Objective: To develop and validate a fully electro-chemo-mechanically coupled computational model for structural batteries

Method: A thermodynamically consistent modelling approach is used.

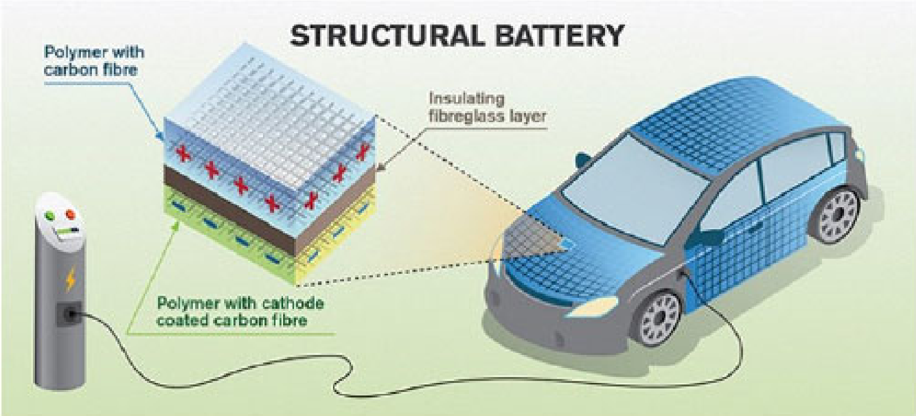
We consider effects of lithium insertion in the transversely isotropic carbon fibres, leading to insertion strains. Further, stress-assisted ionic transport is accounted for in addition to standard diffusion and migration.

Achievements: As a proof of concept, the numerical studies reveal that it is vital to account for two-way coupling in order to predict the multifunctional (i.e. combined electro-chemo-mechanical) performance of structural batteries

Carlstedt D, et al. Submitted, 2020.

Carbon Fibre Composite Structural Batteries: A Review

Objective:
To present the first ever review paper on structural battery composites. Given that the first working structural battery was made in 2010 we wanted to report on the state of the art as we enter the new decade.



Achievements:
A comprehensive overview of research performed on structural battery composites to date. Significant work on the structural battery full cell and its manufacture and validation remains before structural battery composites offer a solution for mass-less energy storage in future electric road, air and sea transport applications. To date, no show-stoppers for the realisation of structural battery composites have been identified.

Asp L., Johansson M., Lindbergh G., Xu J., Zenkert., "Carbon Fibre Composite Structural Batteries: A Review", *Functional Composites and Structures*, Vol 1, 042001, 2019

Accomplishments

Accomplishments

- Improved structural battery electrolyte that can be used with thermal curing;
- Developed parameter based models for predicting mass savings and performance envelopes using structural supercapacitors and batteries compared to conventional materials and batteries on various platforms;
- Performed full life cycle analysis of structural batteries with promising results;
- Developed techniques to produce curved structural power components;
- Developed models to predict the optimum microstructure of structural electrolytes and to predict architecture of consolidated devices;
- Measured and characterised interfacial strength between carbon fibres and the structural battery electrolyte;
- Measured and characterised the longitudinal, transverse and shear moduli of carbon fibres;
- Combined all previous research work on structural batteries in a review paper;
- Created, built, tested and verified a new approach for shape-morphing of stiff carbon fibre composite using electrochemical actuation.

Impact

Impact

- Taken several important steps towards realising structural supercapacitors and batteries;
- Developed suite of structural power modelling tools which will ultimately facilitated both future materials design and certification of structural power devices;
- Shown that structural batteries can save mass on systems level and lead to reduced environmental impact;
- Created a new route for shape-morphing of composites.

Next Steps

Next Steps

- Continue to pursue realising full structural battery cells and characterise electrochemical and mechanical properties;
- Further develop routes for carbon fibre based structural positive electrodes;
- Explore ultra-thin separators for high-power structural batteries;
- Characterise the multifunctional performance of structural battery full cells;
- Further develop shape-morphing composite materials.