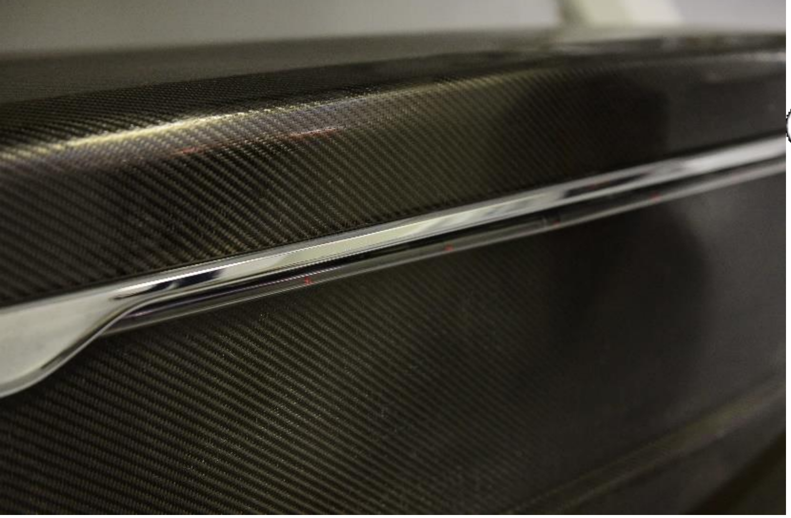

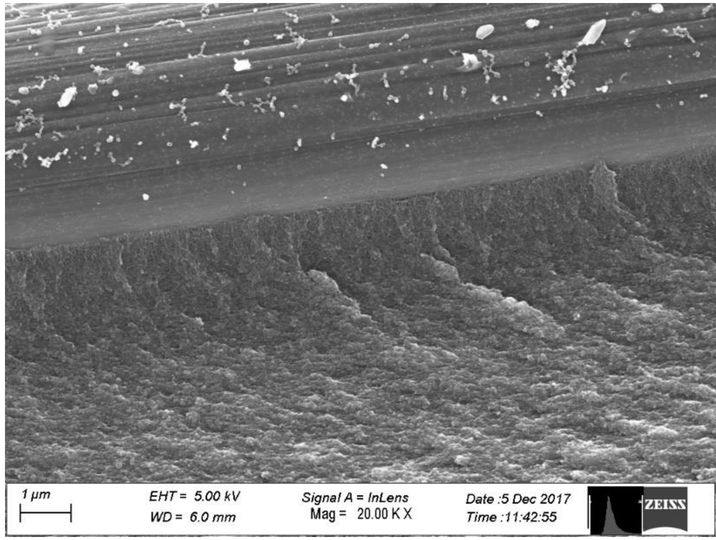

FUTURE CHALLENGES AND INDUSTRIAL ADOPTION STRATEGIES FOR STRUCTURAL SUPERCAPACITORS

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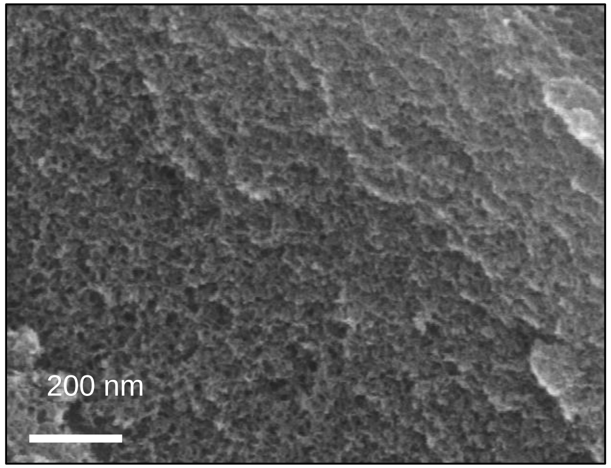
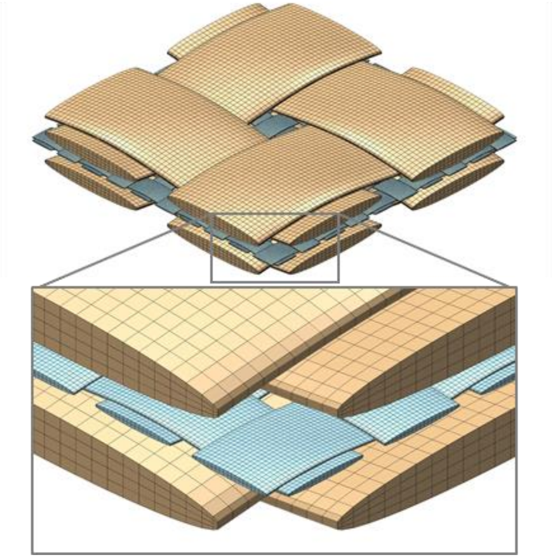
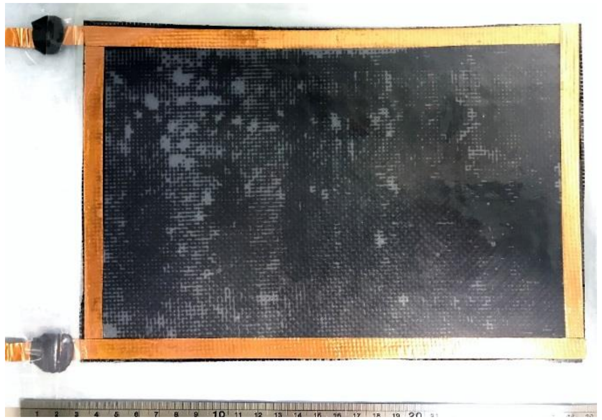
- Potential Adoption Routes
- Conclusions
- Acknowledgements







Introduction and Motivation

Going beyond Smart Materials....

- Conventional *reductionalist* design approach - maximise efficiency of individual subcomponents.
  - ⇒ Difficult compromises;
  - ⇒ Limiting technological advance and stifling innovative design.
- **Different *holistic* approach; structures and materials which simultaneously perform more than one function.**

Smart (Multifunctional Structures)…

Implanting of secondary materials or devices within a parent laminate to imbue additional functionality...

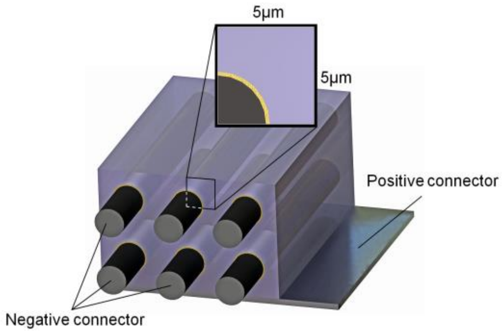
⇒ e.g. embedding devices within structural materials

J. P. Thomas & M. A. Qidwai, JOM. v57 p18-24. 2005.

Multifunctional Materials….

Constituents synergistically and holistically perform two very different roles....

⇒ e.g. a nanostructured carbon lattice carrying mechanical load whilst intercalating lithium ions for electrical energy storage

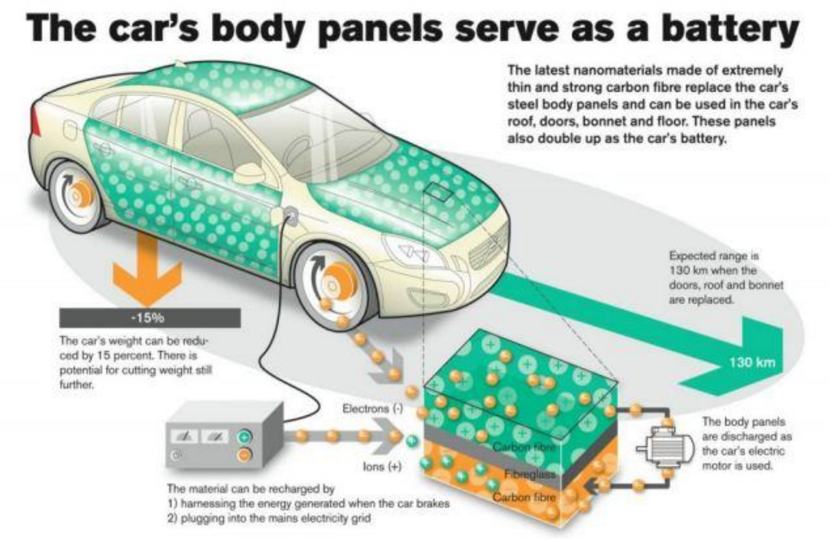


Jacques E., et.al, Electrochemistry Communications, Volume 35, 2013, Pages 65-67.

Motivation for Multifunctional Materials

- We can now tailor composite properties beyond purely the mechanical perspective.
  - ⇒ New and diverse functionalities being added.
- Multifunctional composite materials has potential to revolutionize transportation, portable electronics and infrastructure.
- Focus of this paper is structural supercapacitors:
  - ⇒ Carry mechanical loads whilst storing and delivering electrical energy.

- **Objectives**:
  - ⇒ Overview of the structural supercapacitor research at Imperial College London;
  - ⇒ Outline the near and medium-term challenges for these new materials;
  - ⇒ Suggest industrial adoption strategies.



Multifunctional structural power concept (Volvo Cars)

Multifunctional demonstrator from STORAGE project

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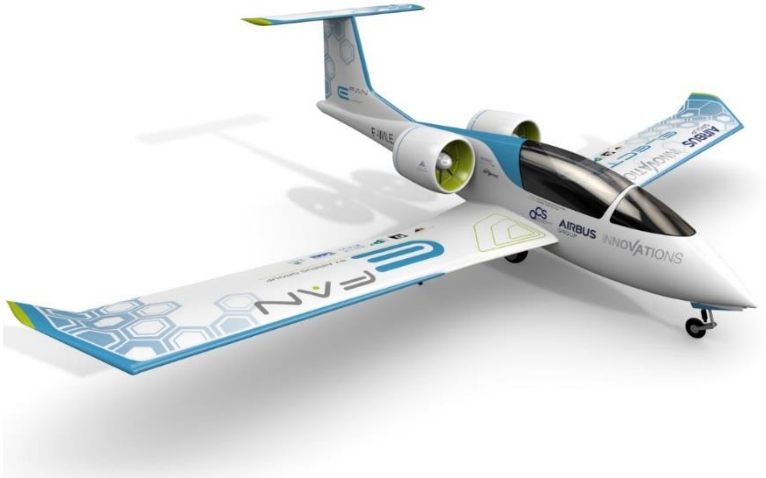
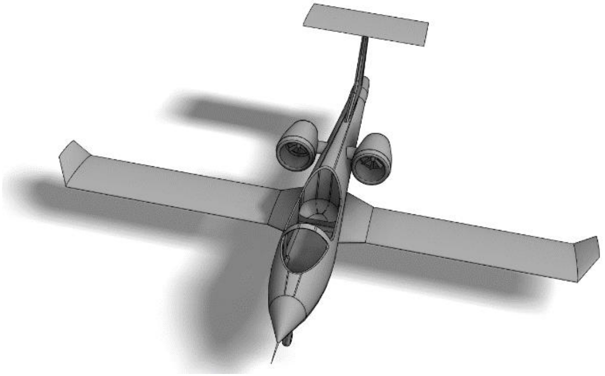
Motivation – Example (E-Fan)

167kg Battery

E-Fan 1.0 (500kg)





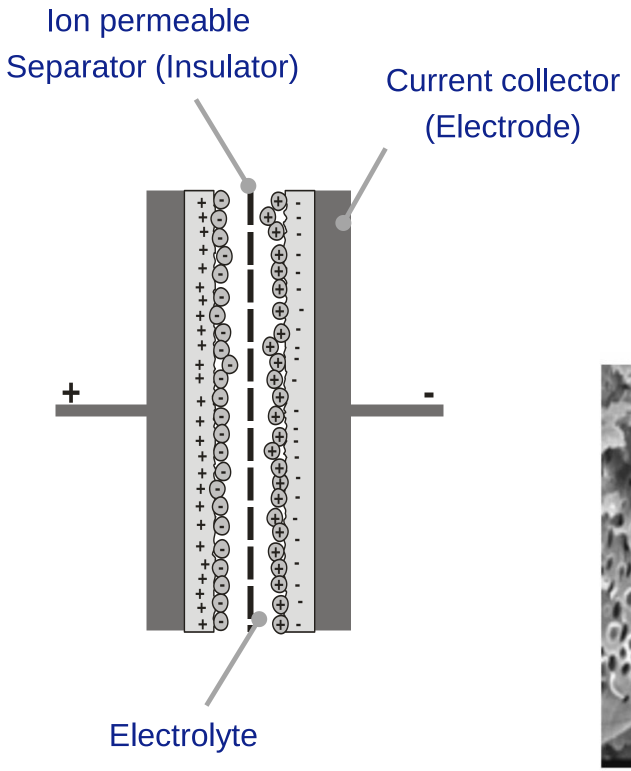
Structure/Systems (333kg)

What electrical performance of the Structural Power Composite (SPC) is required to exceed the performance (i.e. 60 min endurance) of the conventional system (i.e. load-bearing structure + batteries)?

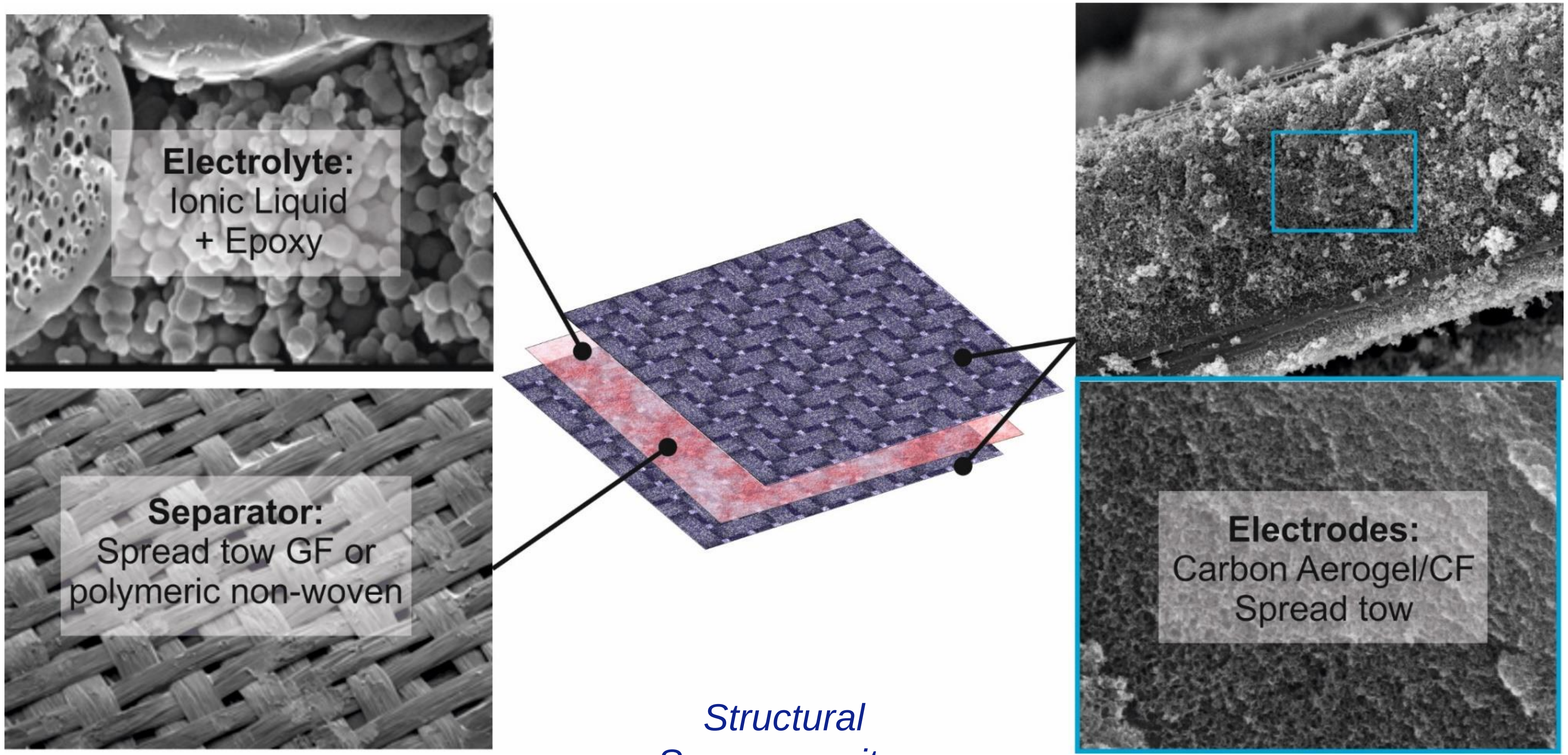
Scenario	Aircraft Mass (kg)	Specific Energy (Wh/kg)	Specific Power (W/kg)
Remove battery , SPC to provide energy *(i.e. reduce aircraft weight).*	333	87	310
Remove battery, replace with SPC *(i.e. aircraft weight maintained)*	500	71	179

Structural Supercapacitors – Imperial College Research

Supercapacitor Device

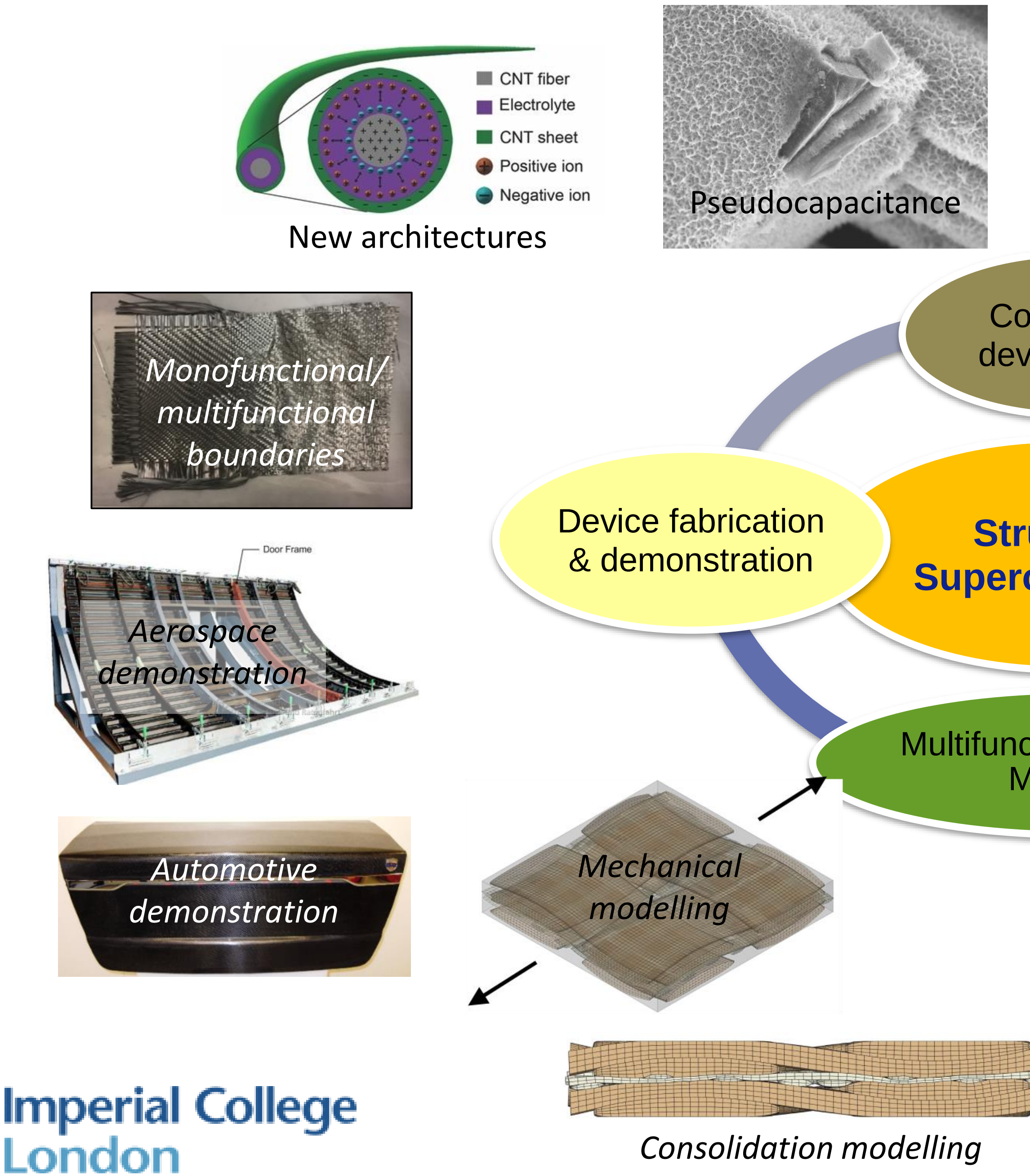


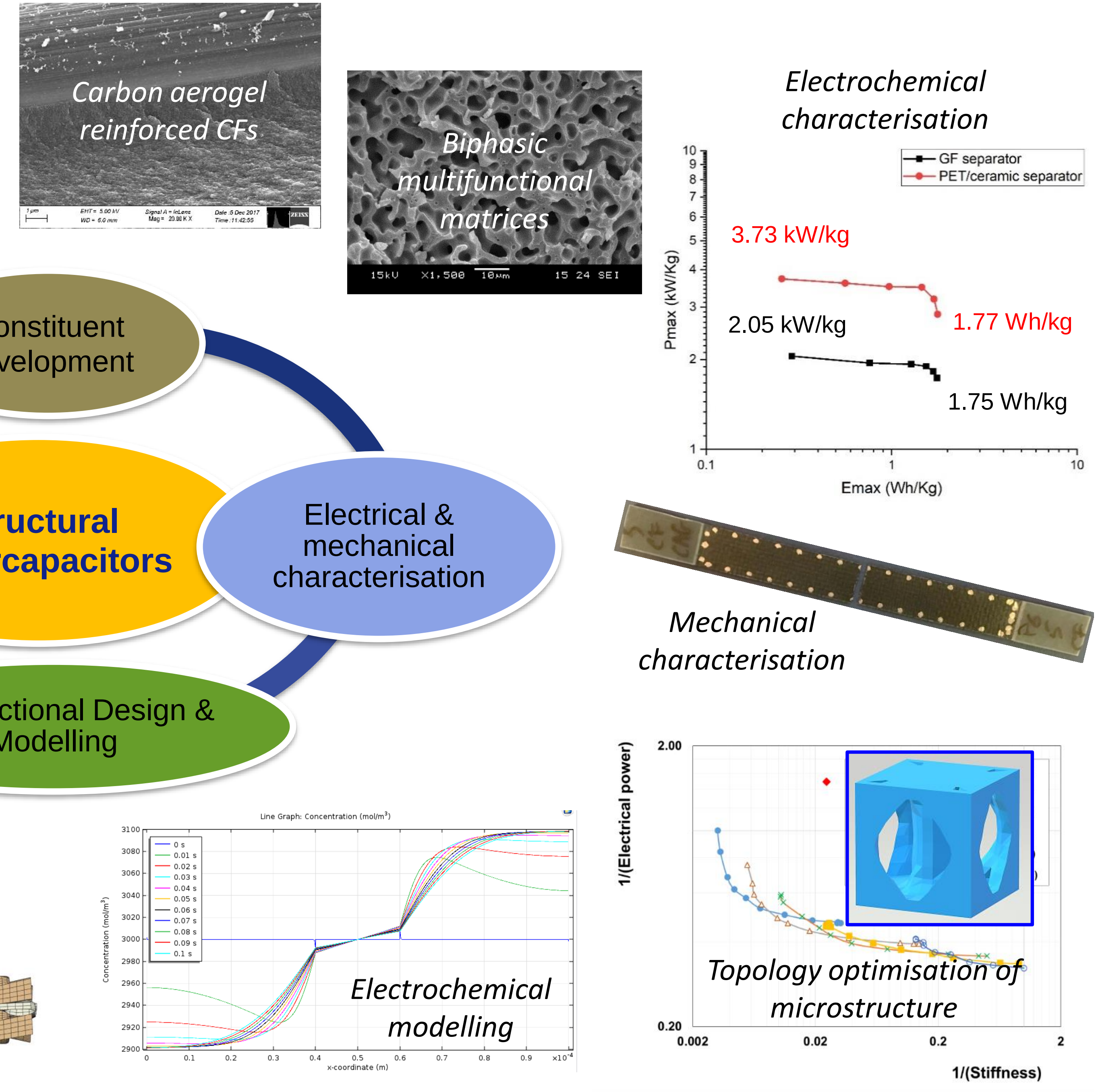
Conventional Supercapacitor



Structural Supercapacitor

Research Streams





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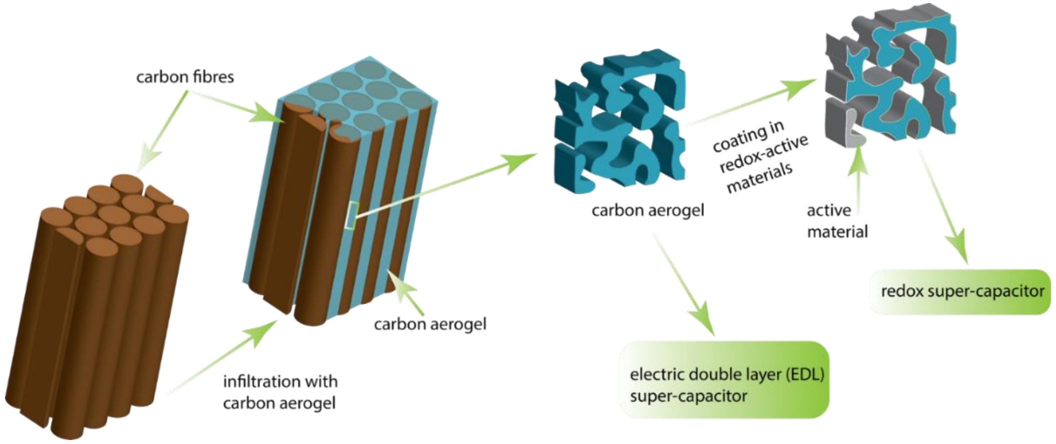
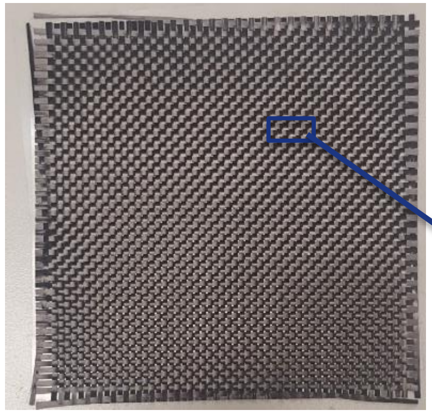
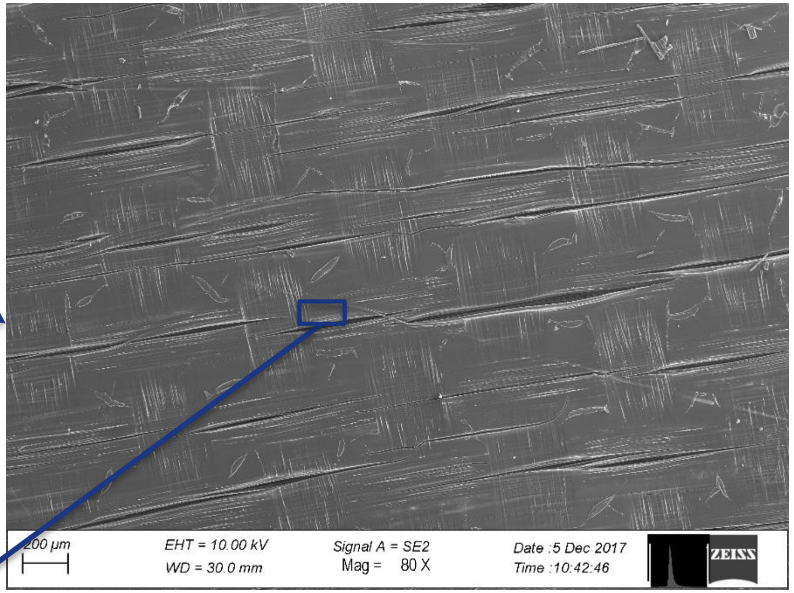
Reinforcement Development



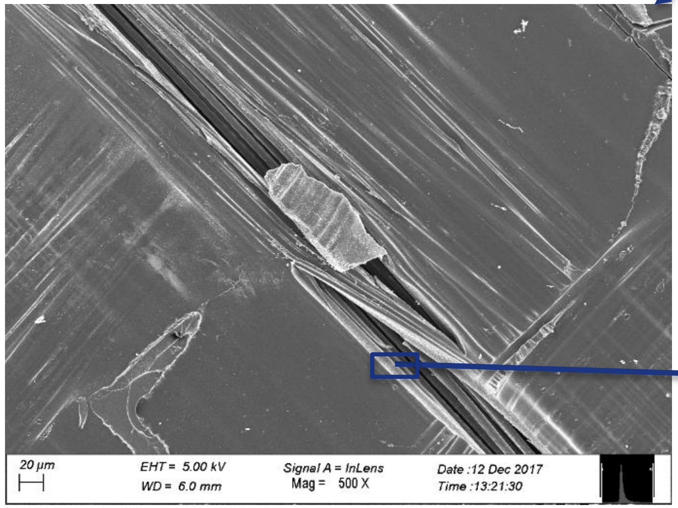


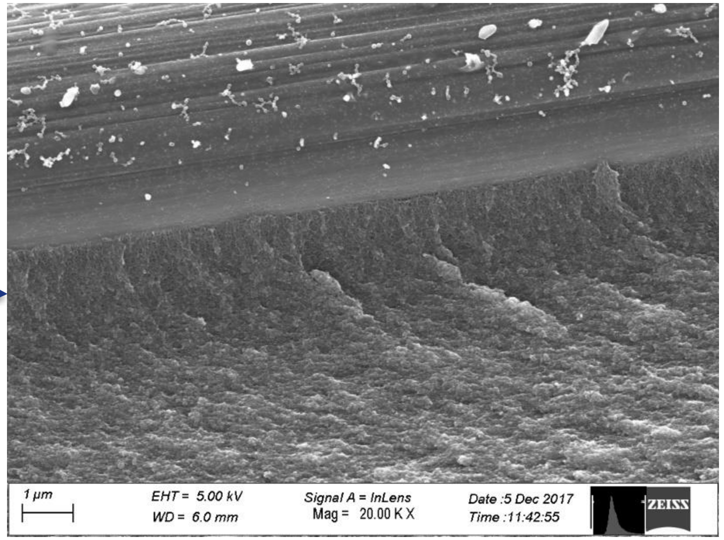


Carbon aerogels possess much higher specific surface areas compared to carbon fibres.

Also high stiffness which is beneficial to the mechanical performance:

- Active materials for electric double layer capacitors
- Scaffold/current collectors for redox active materials: reducing dead weight





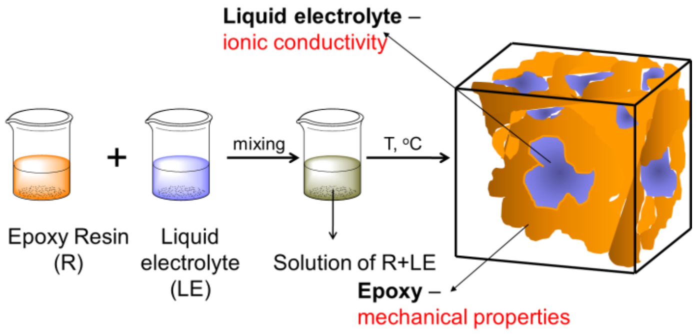
CAG coating of CFs and detailed microstructure

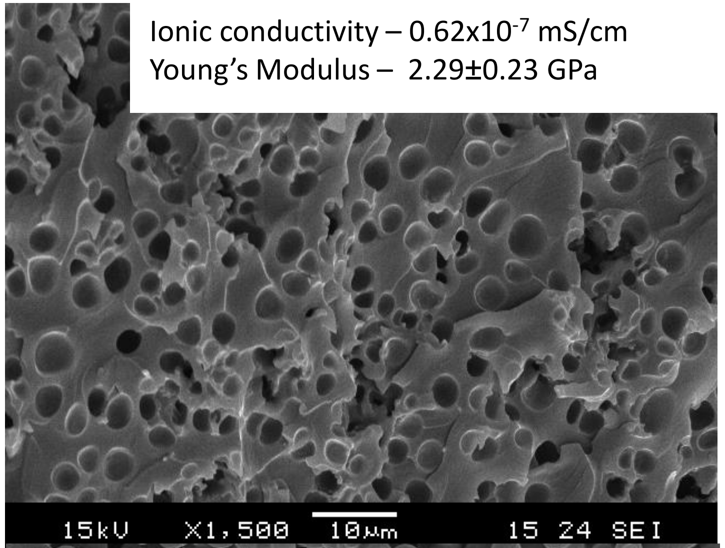
Structural Electrolyte Development

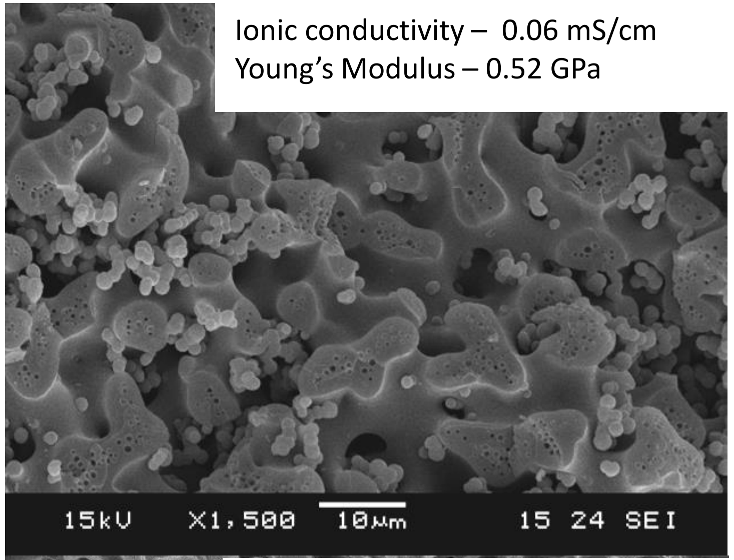
Aspirational multifunctional electrolyte:

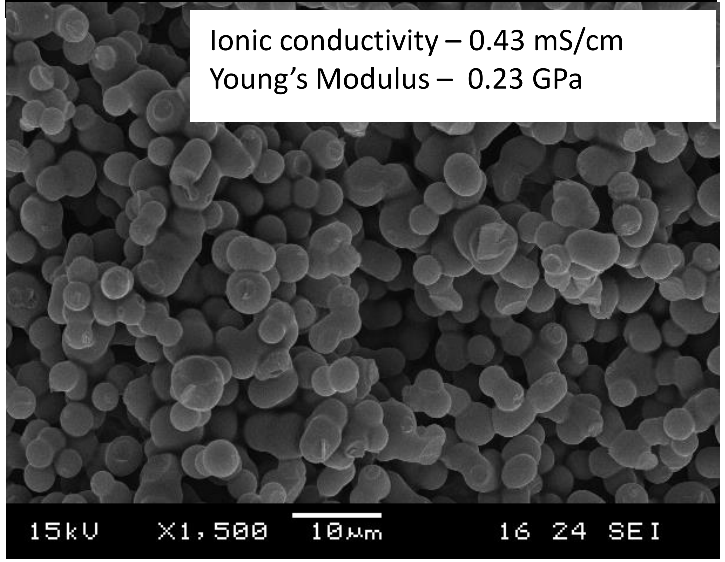
- Ionic conductivity – 1 mS/cm;
- Young's Modulus – 1 GPa.

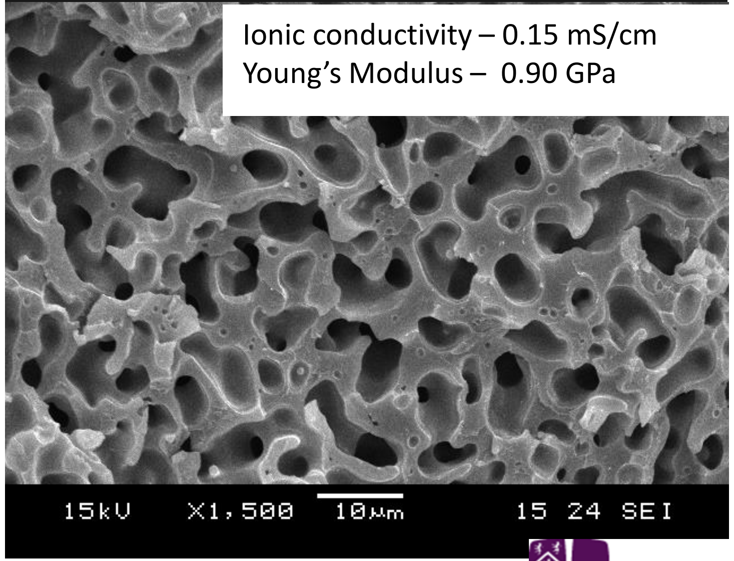
Form a bicontinuous structure with one phase responsible for providing mechanical strength while another ensures ionic conductivity.











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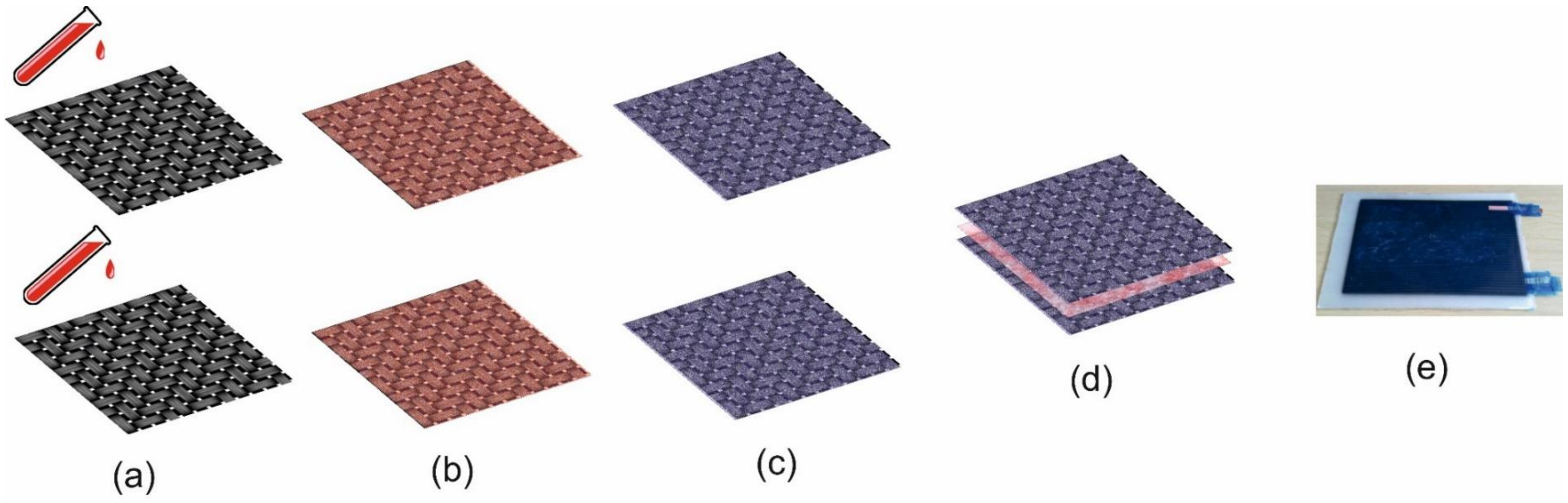
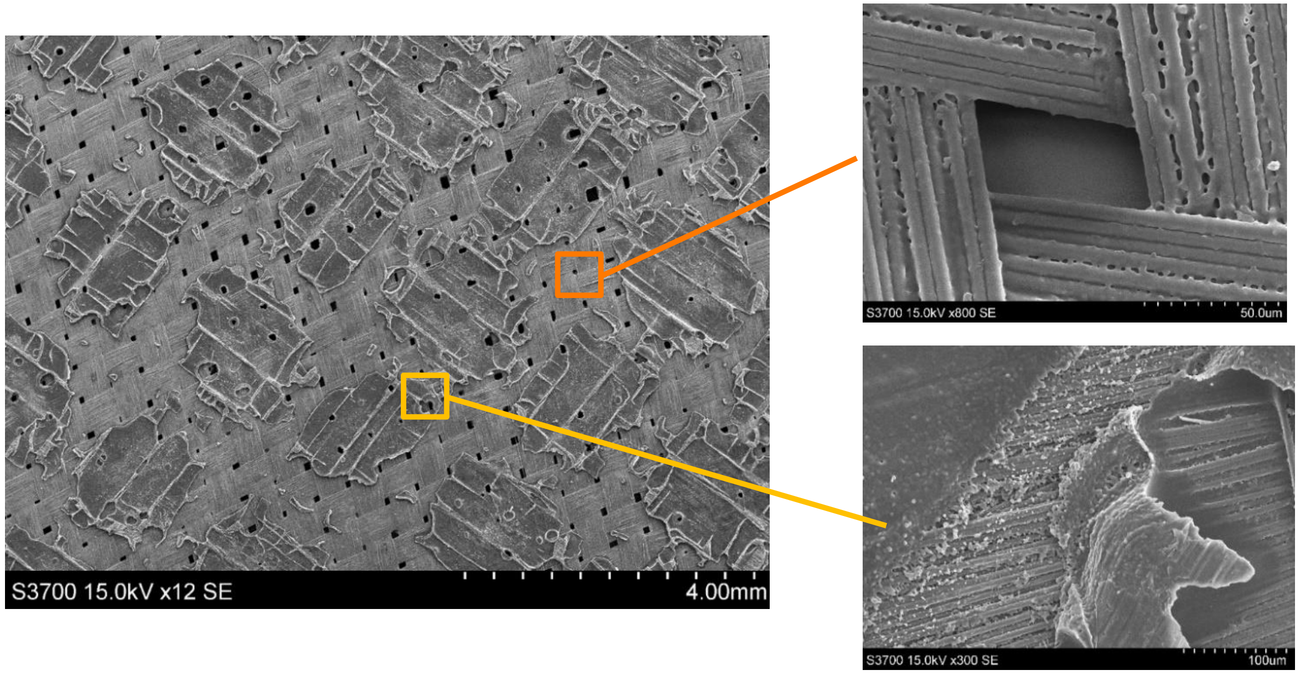
Device Fabrication and Assembly



(a) Infuse individual CF lamina with CAG precursor;
(b) Pyrolyse individual lamina to form the CF/CAG;
(c) Wash CF/CAG lamina;
(d) Assemble device to produce CF/Sep/CF laminate;
(e) Infuse laminate with multifunctional matrix & cure.



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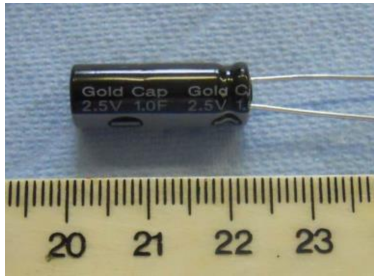
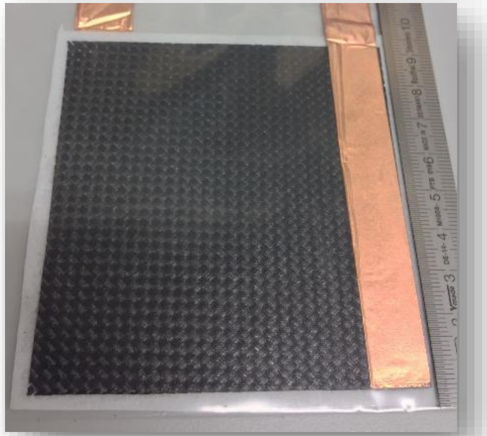
Summary of semi-structural & MF cell performance

Electrodes	Separator	Electrolyte	C (F)	m (g)	V (V)	ESR (Ω)	C* (F/g)	E* (Wh/kg)	P* (kW/kg)
CAG CF 43 gsm	Woven GF (242 μm)	EMI-TFSI	0.68	0.91	2.7	2.66	0.8	0.8	0.8
CAG CF 43 gsm	**PET/ceramic (23 μm)**	**EMI-TFSI**	**1.01**	**0.36**	**2.7**	**1.49**	**3.1**	**3.2**	**3.4**
CAG CF 43 gsm	Woven GF (50 μm)	MF (40%)	0.34	0.39	2.7	7.45	0.9	0.9	0.6
CAG CF 43 gsm	**PET/ceramic (23 μm)**	**MF (40%)**	**0.51**	**0.36**	**2.7**	**4.80**	**1.4**	**1.4**	**1.1**
Maxwell BCAP0150[1], length = 50 mm, dia. = 25 mm			*150*	*32*	*2.7*	*14 mΩ*	*4.7*	*4.7*	*4.1*



Conventional supercapacitor

Γ=4.7Wh/kg & P=4.1kW/kg



*Normalised to active mass

C arbon fabrics	138 mg
A erogel	62 mg
S eparator (PC)	53 mg
E lectrolyte	107 mg

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EPSRC
Engineering and Physical Sciences Research Council

Future Challenges

Future Challenges – Multifunctional Design

- Conventional design approach
  - ⇒ Implement new properties and then characterize how the improved performance compares to that of the COTS (Current Off The Shelf) for the same function.
- However, structural power material cannot…
  - ⇒ Offer better mechanical load-carrying capability than a fully optimized conventional structural material
  - ⇒ Offer better electrochemical performance than a conventional battery or supercapacitor.
- ***Taking a holistic view during design is vital***
  - ⇒ Structural power materials partially undertake the role of both the structural components (e.g. spars or skins) and the energy storage (e.g. battery, supercapacitor, etc.);
  - ⇒ Hence a system approach to design, rather than the conventional compartmentalized approach, should be followed.
- Structural Power Materials also offer
  - ⇒ Localization of power sources (i.e. reducing wiring)
  - ⇒ Opportunities to tailor mass distribution across a platform.
- **Need to capture this within a new design methodology**

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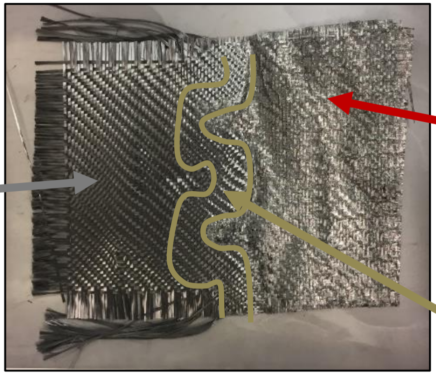
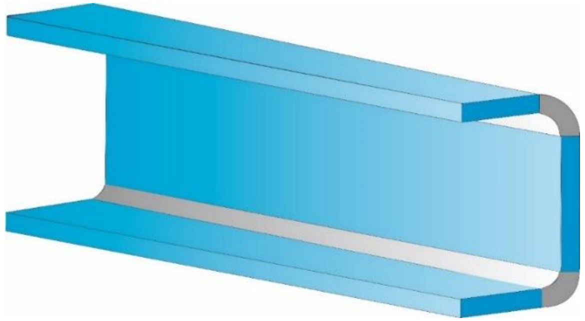
EPSRC Engineering and Physical Sciences Research Council

Future Challenges – Scale-Up and Fabrication

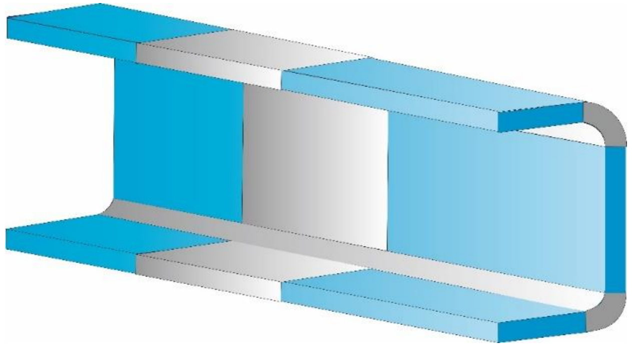
- Fabrication methodologies for structural power materials very different to conventional approaches.
- Melding of polymer composite manufacture and electrochemical device fabrication.
  - ⇒ Any exposure of the matrix/electrolyte to ambient moisture is critical to electrochemical performance.
  - ⇒ ‘Moisture-free’ composite fabrication required
- Fabrication of curved components present additional challenges:
  - ⇒ Currently being addressed through the development of masking of fold lines/barriers, to permit monofunctional and multifunctional domains.
  - ⇒ Investigating as a route to achieve continuity of carbon-fibres across monofunctional/multifunctional boundaries.



Fabrication demonstration using barriers



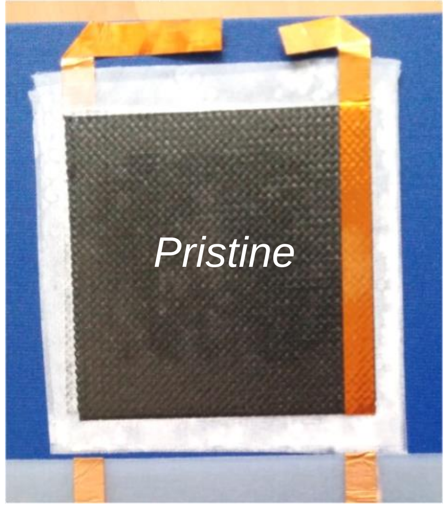
Multifunctional web and cap
Monofunctional fold-lines



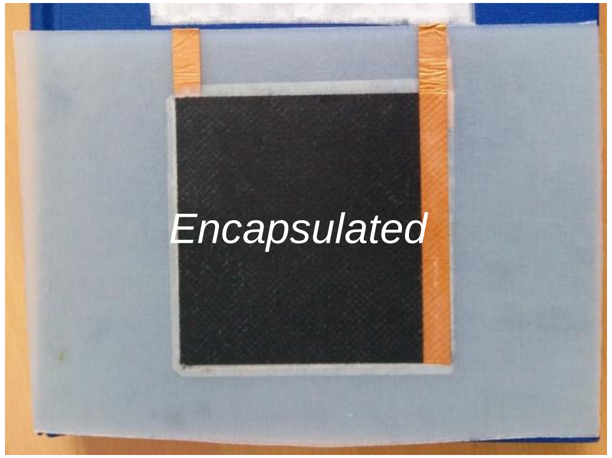
Multifunctional web and cap
Continuity across monofunctional loading pads

Future Challenges - Encapsulation

- Critical near-term challenge is how to encapsulate the structural power material.
- Isolate from the surrounding systems, conventional structure, and ultimately the environment, whilst still transferring mechanical load across the monofunctional/multifunctional interfaces.
- Conventional energy storage devices are encased in inert, insulating sheaths.
- Electrolyte phase (Ionic liquid) is leached out by the uncured epoxy, leading to considerable loss of electrical performance.



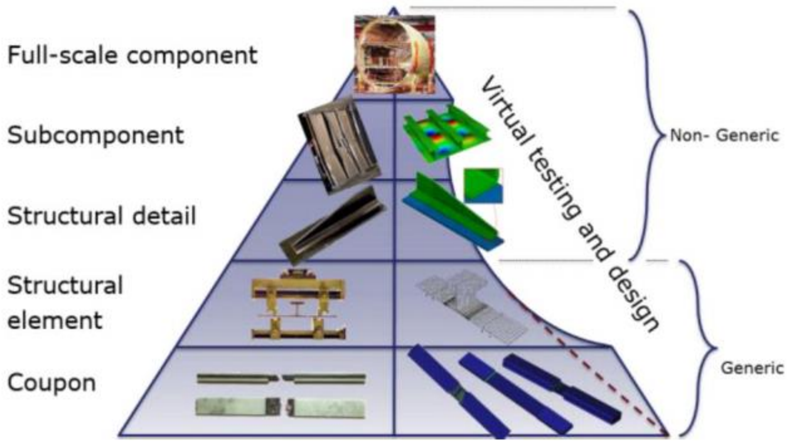
2 GF+ MTM57 B-staged for 30 min, at 80°C

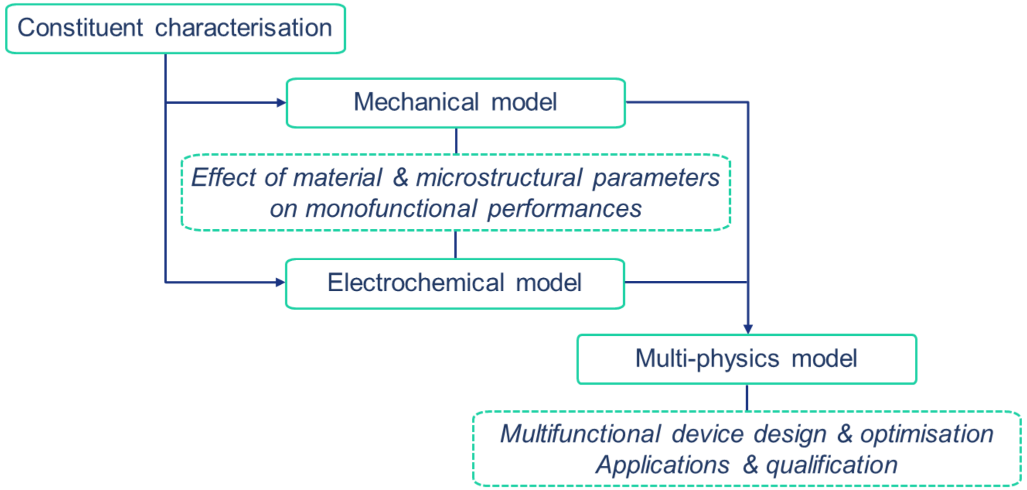


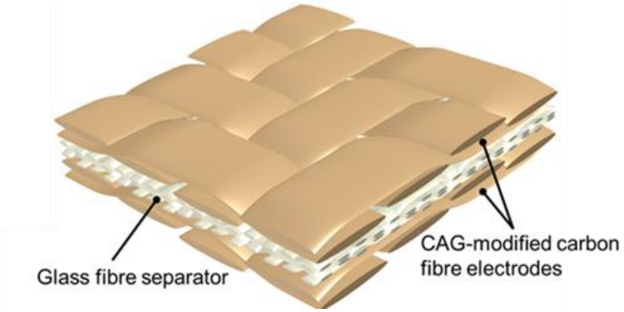
Capacitance (60% drop) & ESR (90% rise)

Future Challenges – Certification & Predictive Modelling

- Most significant hurdle is that of certification, particularly for aerospace applications.
  - ⇒ Conventional structural materials are required to demonstrate airworthiness through the "Rouchon pyramid".
- Structural power materials would not only have to be mechanically certified, but also electrochemically too.
  - ⇒ Any mechanical/electrochemical interactions (e.g. mechanical cycling inducing damage that reduces the electrical performance) needs to be considered.
- Best addressed through developing predictive modelling
  - ⇒ Development of finite element models which can predict both mechanical and electrochemical behavior, and any coupling interactions.







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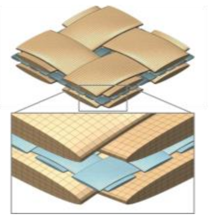
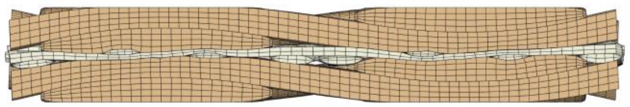
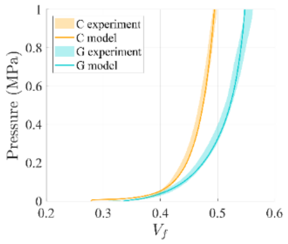
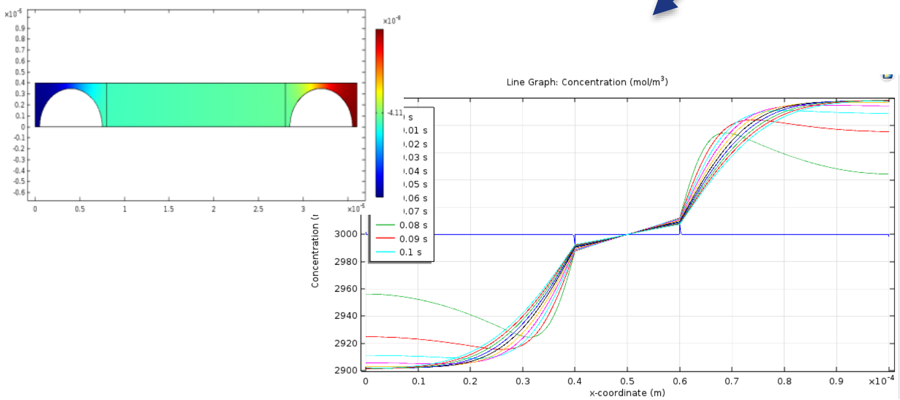
Future Challenges – Predictive Modelling Strategy



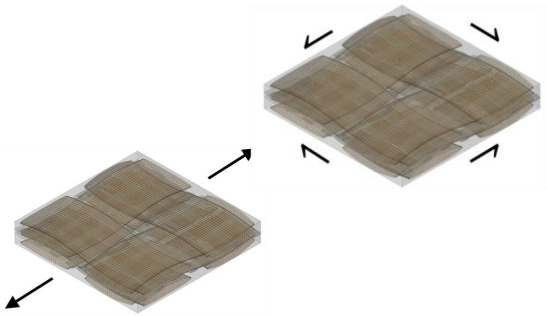


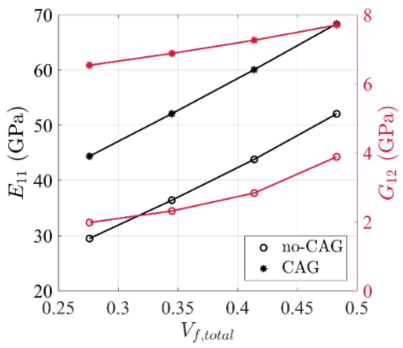


Consolidation modelling



Electrochemical Modelling





Mechanical Modelling

- *Provide a framework to support certification of structural power devices*
- *Couple electrical and mechanical models*

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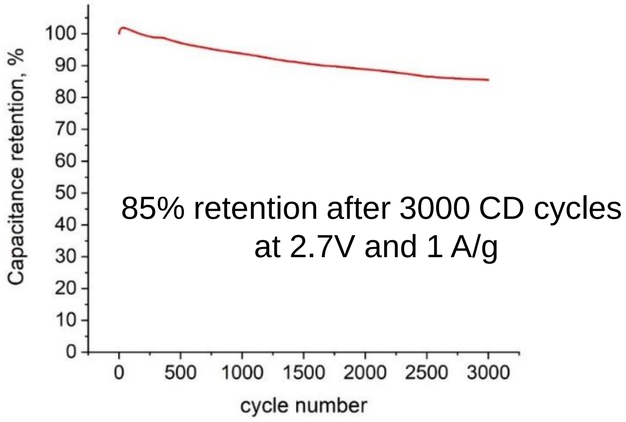
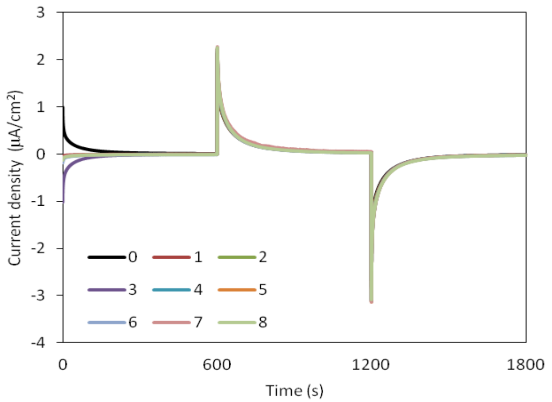
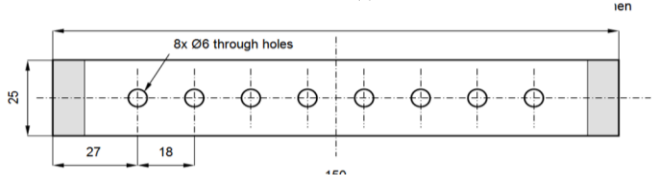
Future Challenges – In-service Conditions

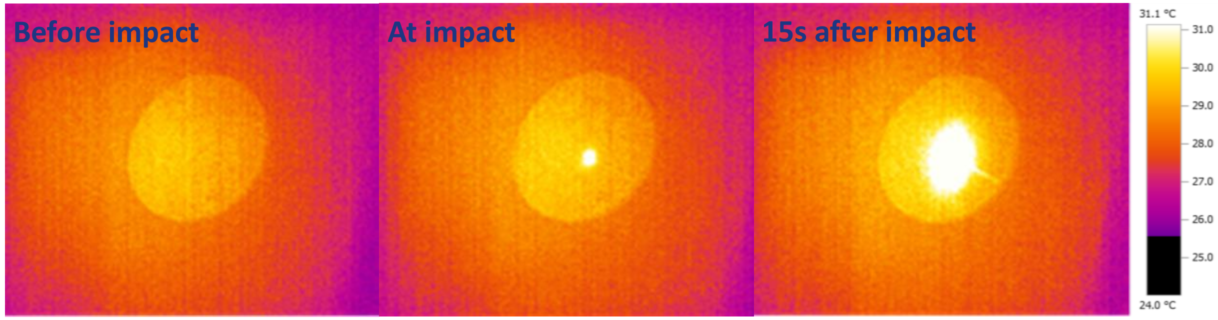
- Range of in-service requirement and conditions to which structural power materials could be exposed, and would be required to tolerate.
- These include
  - ⇒ Cycling (both mechanical and electrical)
  - ⇒ Temperature extremes,
  - ⇒ Fire resistance
  - ⇒ Machining/Finishing
  - ⇒ Impact and Damage Tolerance.
  - ⇒ Inspection/Repair/Disposal



Cyclic performance







Local heating following penetrative impact

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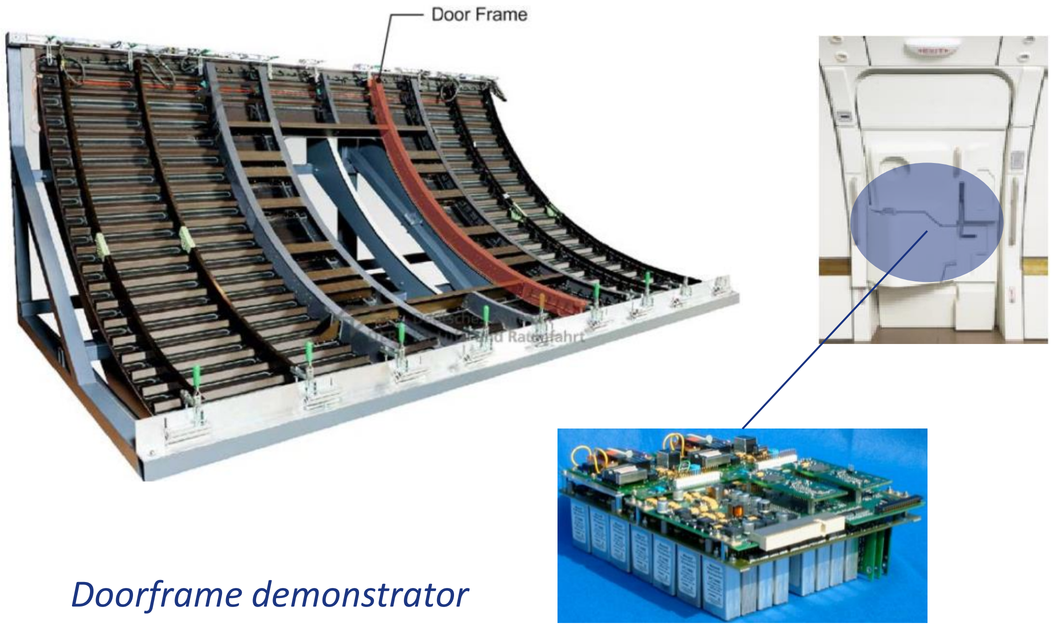
Drilling damage

Potential Adoption Routes

- Structural power is still a very immature technology.
- Performance is too low to replace existing propulsion (aerospace and automotive)
- More reasonable target is to replace auxiliary power sources, such as to reduce the electrical load on main power sources.
- Automotive
  - ⇒ Utilize in secondary sources (stop/start battery, etc);
  - ⇒ Focus on panels and non-safety critical applications.
- Aerospace
  - ⇒ Cabin applications (benign temperature regime);
  - ⇒ Powering seat-back personal displays, etc;
  - ⇒ Local power sources for safety equipment;
  - ⇒ Systems and electronics boxes.
- Other Sectors
  - ⇒ Electric bicycles – energy recovery, etc;
  - ⇒ Mobile electronics.

Volvo bootlid demonstrator from STORAGE project



Doorframe demonstrator from SORCERER

Conclusions

- Structural power composites is an exciting emerging technology for transportation and portable electronics.
- Current performance - *c.f.* conventional supercapacitor at device level (4.7Wh/kg & 4.1kW/kg)
  - ⇒ *3.2Wh/kg & 3.4kW/kg (semi-structural);*
  - ⇒ *1.4Wh/kg & 1.1kW/kg (structural).*
- Still considerable technical hurdles to be addressed, but the outlook is promising.
  - ⇒ *Multifunctional Design*
  - ⇒ *Scale-up and Fabrication*
  - ⇒ *Encapsulation*
  - ⇒ *Certification and Predictive Modelling*
  - ⇒ *In-service Conditions*
- Early adoption routes – auxiliary applications and power sources (aircraft cabin)
- My personal view – structural power, and the generic concept of truly multifunctional materials, is such an simple idea which will provide huge performance benefits and design freedom, it's clearly a case of ***when*** not ***if*** it is widely adopted.

- ***In 50 years time, we won't be using discrete monofunctional batteries, we will build structures from multifunctional materials with innate electrical energy storage.***

Acknowledgements

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- *Ex-researchers* - Habtom Asfaw, Guohui Zhang, & Kaan Bilge
- *Collaborators* - University of Durham, University of Bristol, KTH (Sweden), Chalmers (Sweden), IMDEA (Spain)