

FUTURE CHALLENGES FOR STRUCTURAL POWER COMPOSITES

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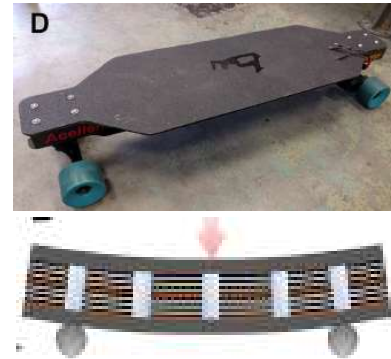
Going beyond Smart Materials....

- Conventional *reductionalist* approach to design - maximise efficiency of individual subcomponents.
 - ⇒ Difficult compromises;
 - ⇒ Limiting technological advance and stifling innovative design.
- Different *holistic* approach; structures & 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



Fu-Kuo Chang et al, *J Power Sources*, v414. 2019.



Thomas & Qidwai, *JOM*, v57. 2005.

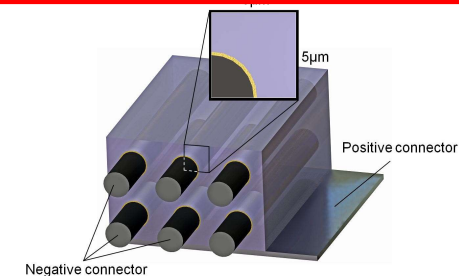
Multifunctional Materials....

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

⇒ e.g. a nanostructured carbon lattice carrying mechanical load whilst storing electrochemical energy.



Greenhalgh, E, et.al, *ICCM22*, 2019.



Jacques E., et.al, *Electrochemistry Communications*, v35, 2013.

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 presentation is structural supercapacitors:

⇒ Carry mechanical loads whilst storing and delivering electrical energy.

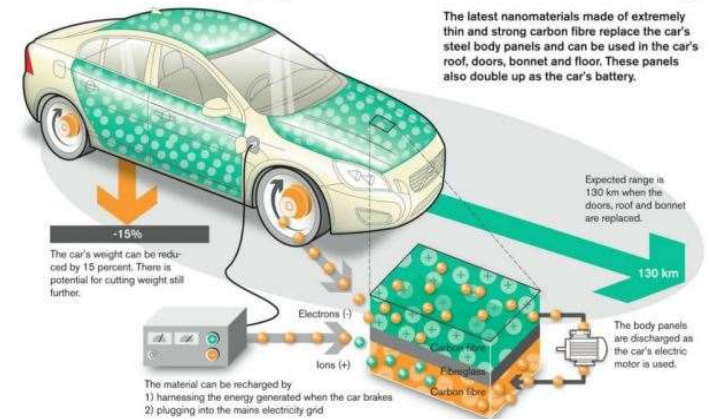
- **Objectives:**

⇒ 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.

The car's body panels serve as a battery



Multifunctional structural power concept (Volvo Cars)

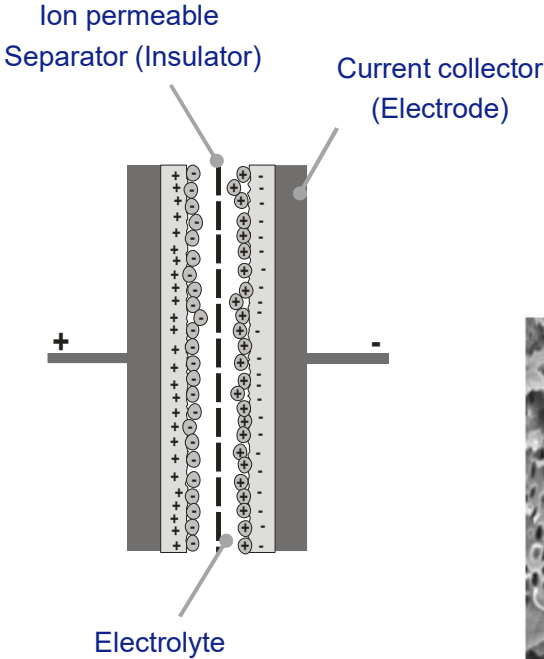
Multifunctional demonstrator from STORAGE project



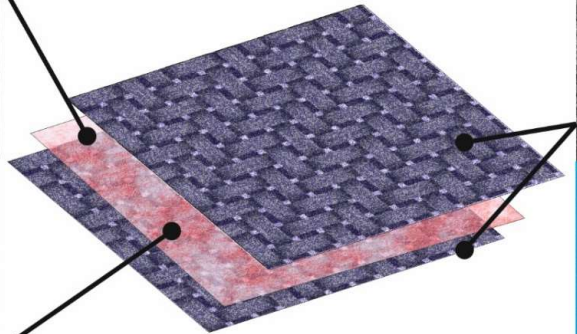
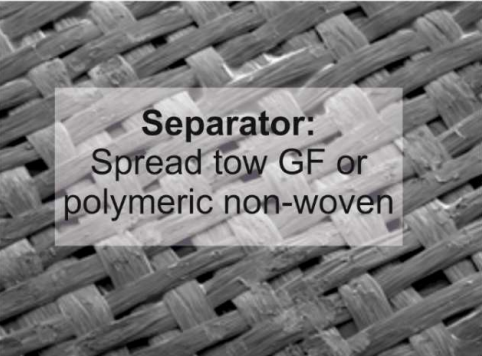
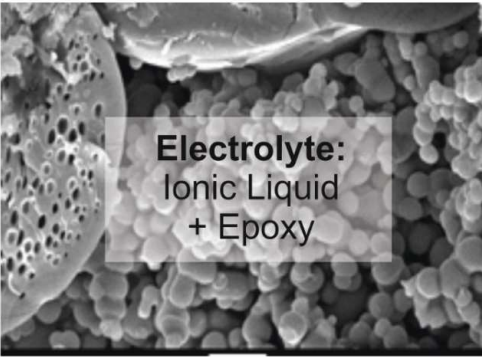


**Structural Supercapacitors –
Imperial College Research**

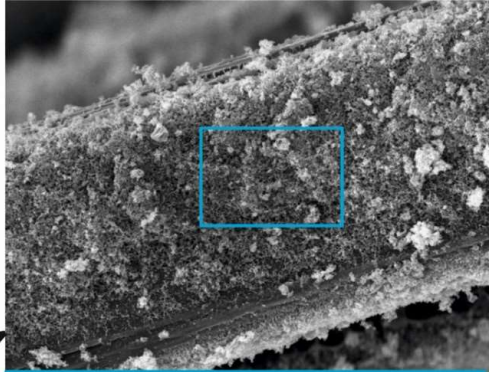
Supercapacitor Device



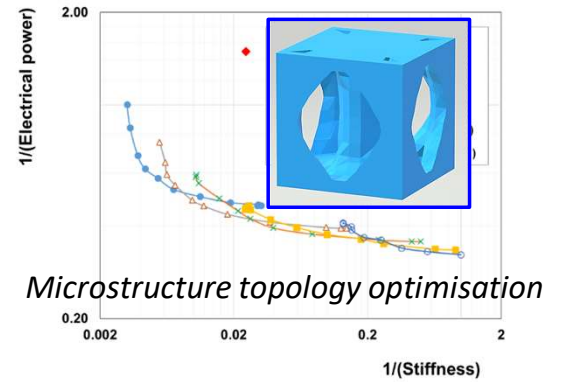
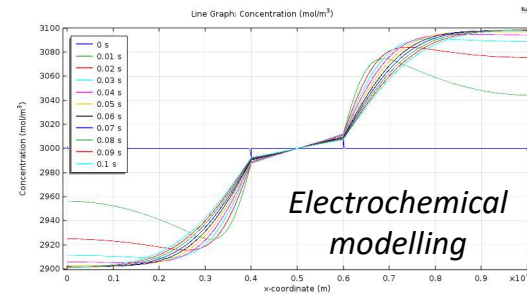
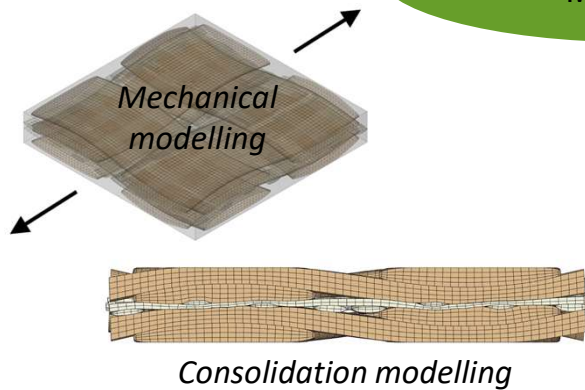
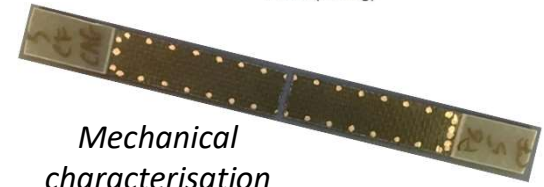
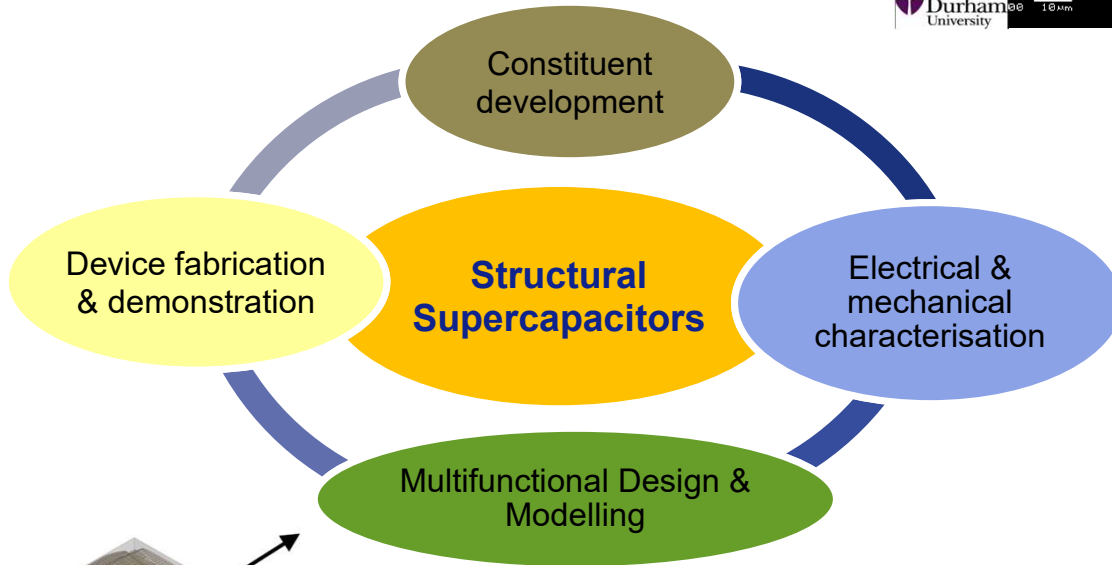
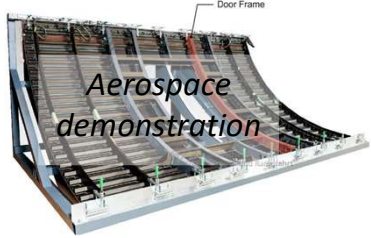
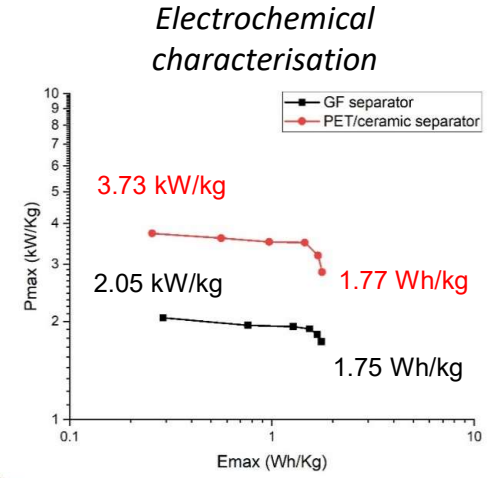
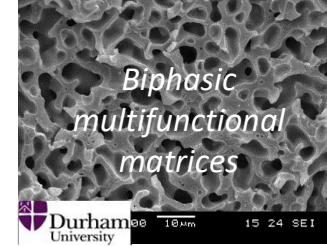
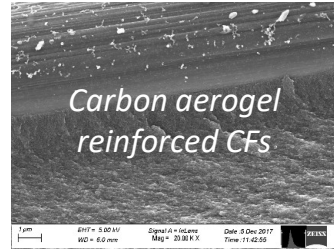
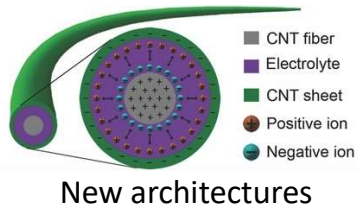
Conventional Supercapacitor



Structural Supercapacitor

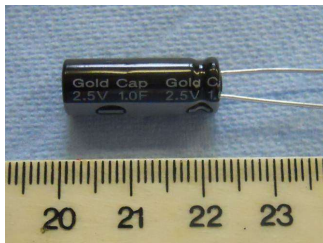


Research Streams

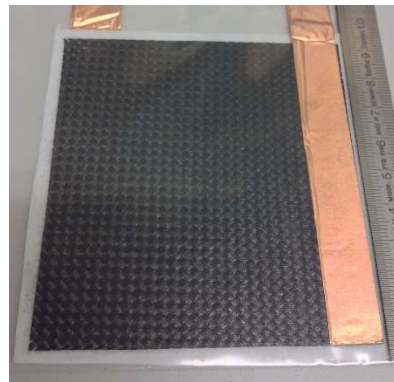


Summary of semi-structural & MF cell performance

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 μ m)	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 μ m)	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
<i>Maxwell BCAP0150¹, length = 50 mm, dia. = 25 mm</i>			<i>150</i>	<i>32</i>	<i>2.7</i>	<i>14 mΩ</i>	<i>4.7</i>	<i>4.7</i>	<i>4.1</i>



Conventional supercapacitor
 $\Gamma=4.7\text{Wh/kg}$ & $P=4.1\text{kW/kg}$



*Normalised to active mass

Carbon fabrics	138 mg
Aerogel	62 mg
Separator (PC)	53 mg
Electrolyte	107 mg



Future Challenges

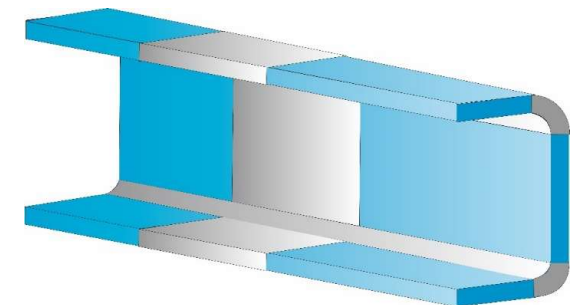
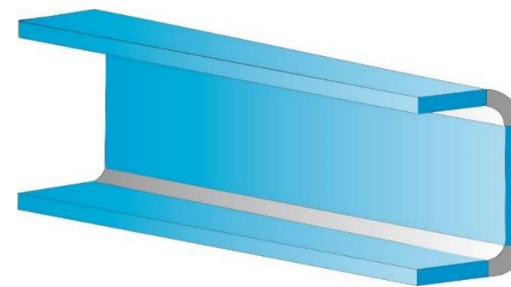
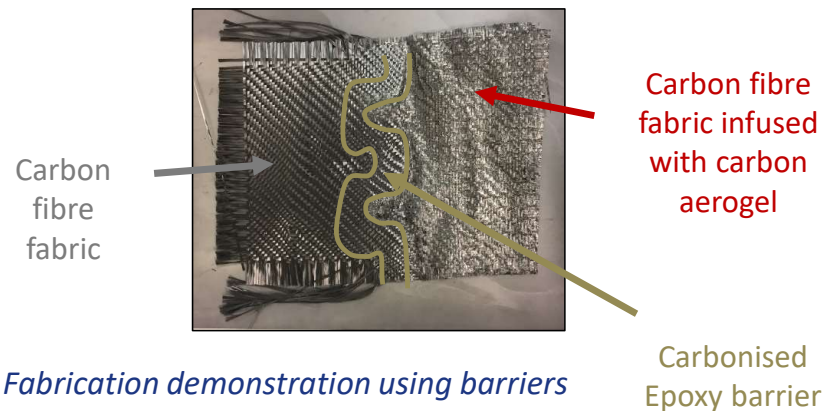
Future Challenges – Multifunctional Design

- 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**



Future Challenges –Fabrication

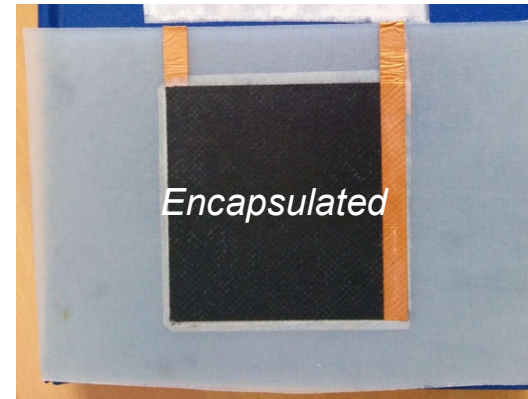
- Fabrication methodologies for structural power materials very different to conventional approaches.
- Melding of polymer composite manufacture and electrochemical device fabrication.
 - ⇒ Any exposure of the matrix/electrolyte to ambient moisture is critical to electrochemical performance.
 - ⇒ ‘Moisture-free’ composite fabrication required
- Fabrication of curved components present additional challenges:
 - ⇒ Currently being addressed with University of Bristol 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.



Future Challenges - Encapsulation



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



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

- 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.

Future Challenges – Current Collection / Scale-up

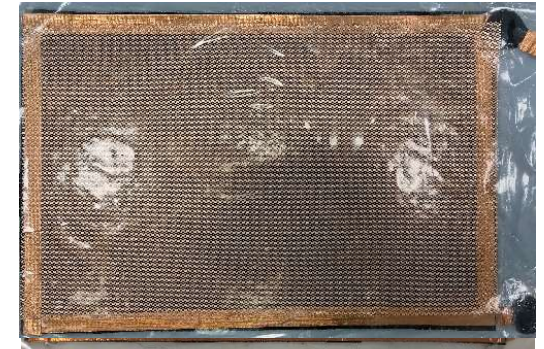


10 mm



Electrolyte: EMIM TFSI
 Area of electrodes: 0.785 cm²
 Area of separator: 1.13 cm²

All values normalised by device mass
 (CAG/C-weave + GF separator + IL to fill all pores)



Swagelok cell (1 cm diameter)

Lab scale (16 cm²)

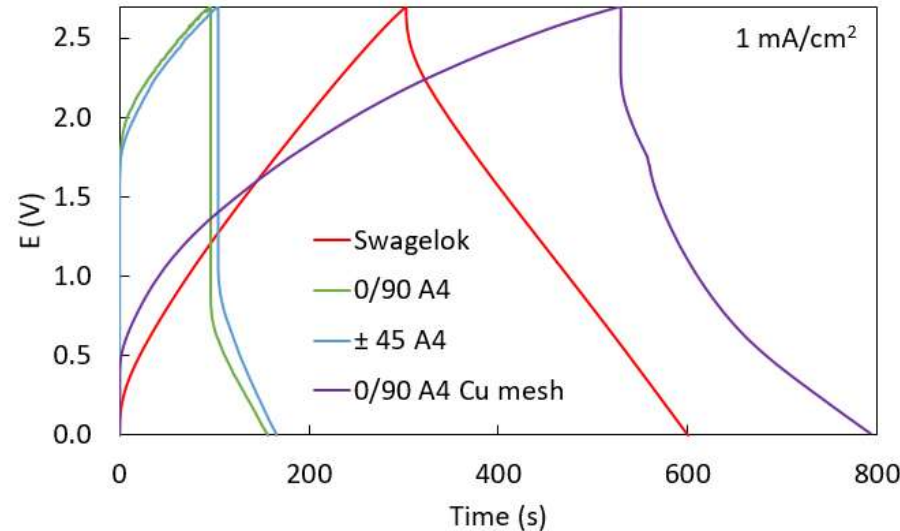
Component scale (446 cm²)

Swagelok (m = 51 mg)

$C^* = 1.73 \text{ F/g}$

$E^*_{\text{max}} = 1.75 \text{ Wh/kg}$

$P^*_{\text{max}} = 2.05 \text{ kW/kg}$



Plain

Cu Mesh

0/90 A4 (m = 32 g)

0/90 A4 (m = 40 g)

$C^* = 0.82 \text{ F/g}$

$C^* = 1.3 \text{ F/g}$

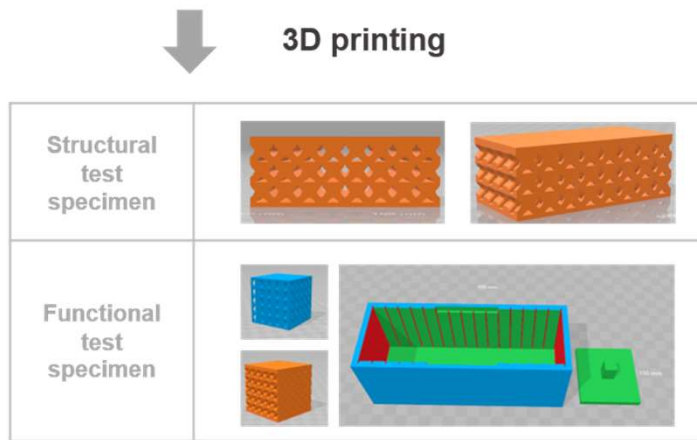
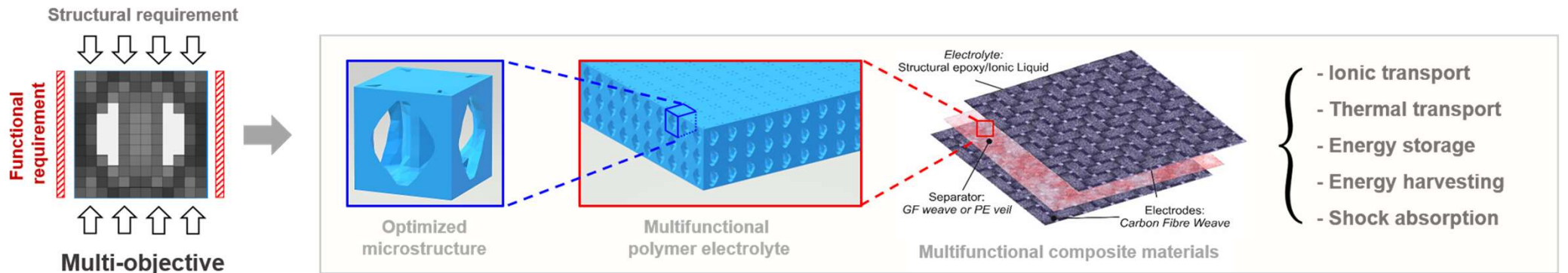
$E^*_{\text{max}} = 0.83 \text{ Wh/kg}$

$E^*_{\text{max}} = 1.3 \text{ Wh/kg}$

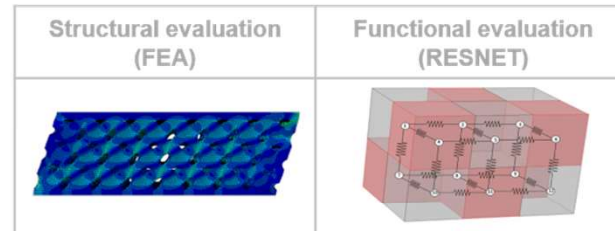
$P^*_{\text{max}} = 0.027 \text{ kW/kg}$

$P^*_{\text{max}} = 0.066 \text{ kW/kg}$

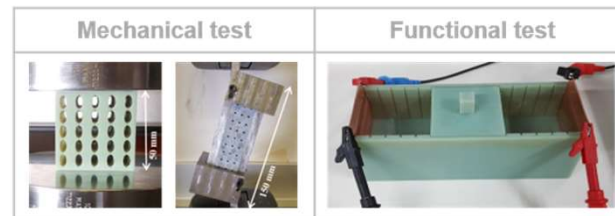
Future Challenges – Multifunctional Material Design



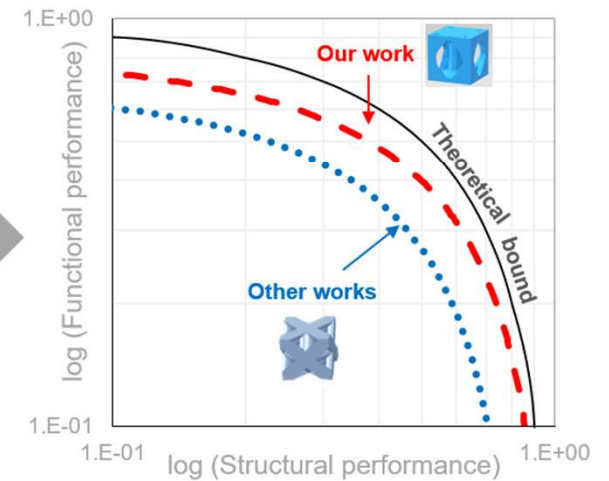
Numerical investigation



Experimental investigation

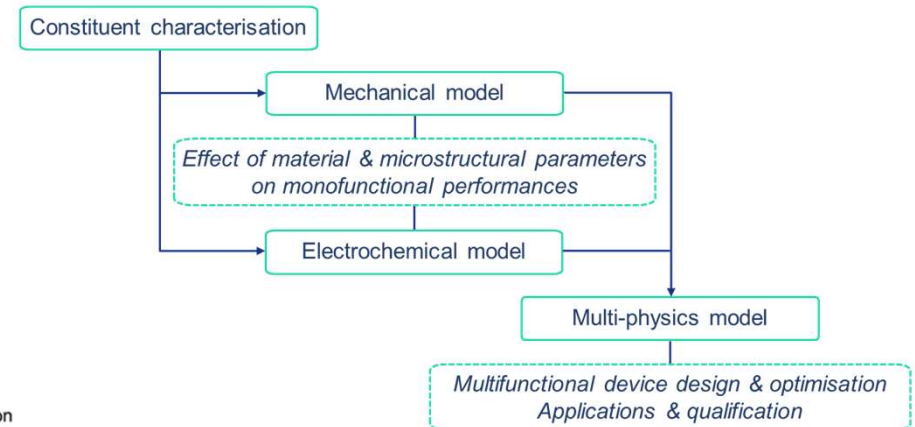
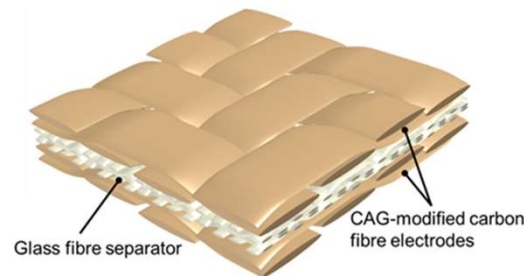
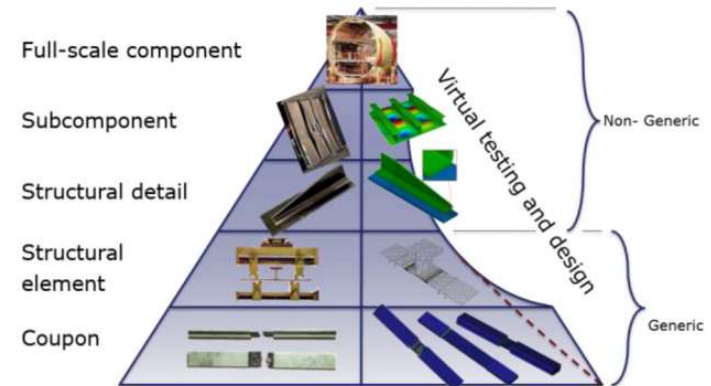


Outcome

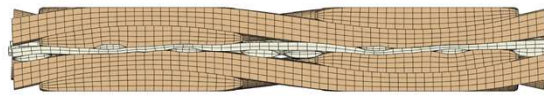
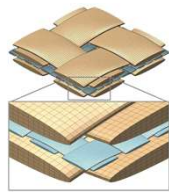


Future Challenges – Certification & Predictive Modelling

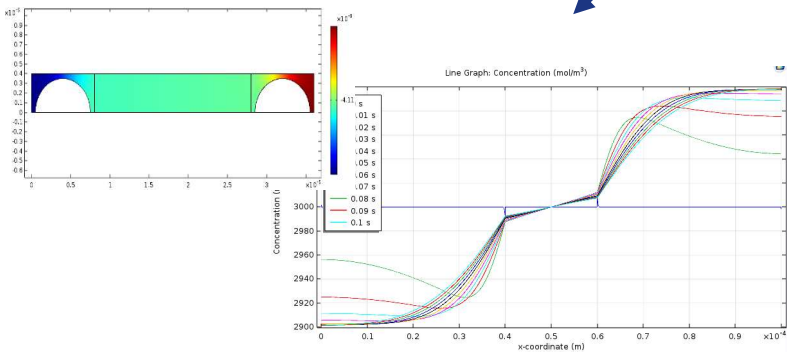
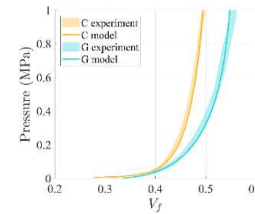
- Most significant hurdle is that of certification, particularly for aerospace applications.
 - ⇒ Conventional structural materials are required to demonstrate airworthiness through the “Rouchon pyramid”.
- Structural power materials would not only have to be mechanically certified, but also electrochemically 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.



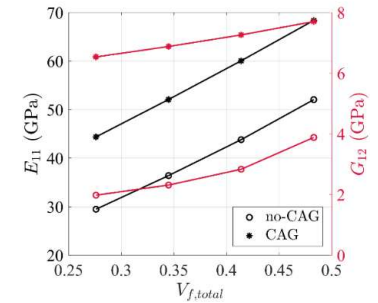
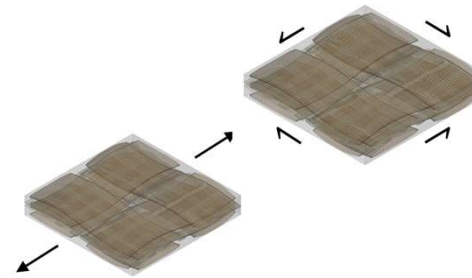
Future Challenges – Predictive Modelling Strategy



Consolidation modelling



Electrochemical Modelling



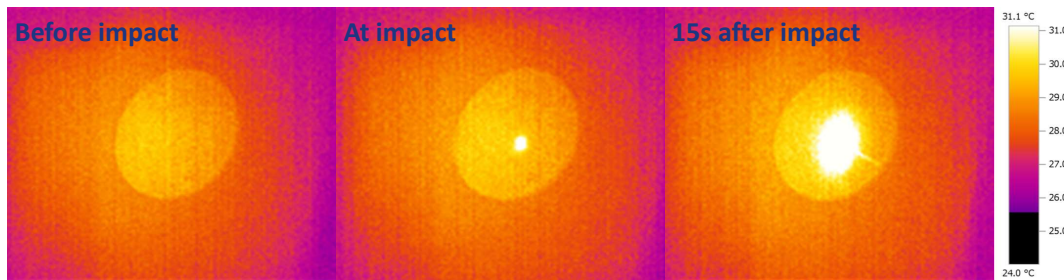
Mechanical Modelling



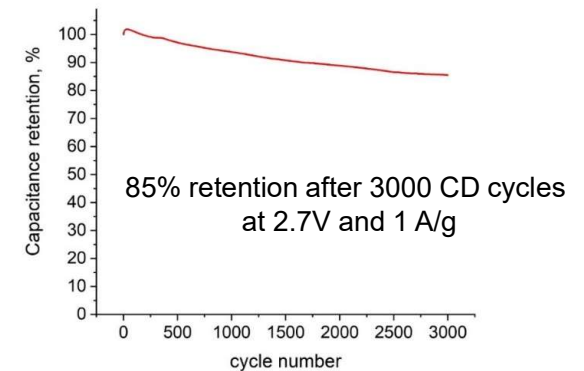
- Provide a framework to support certification of structural power devices
- Couple electrical and mechanical models

Future Challenges – In-service Conditions

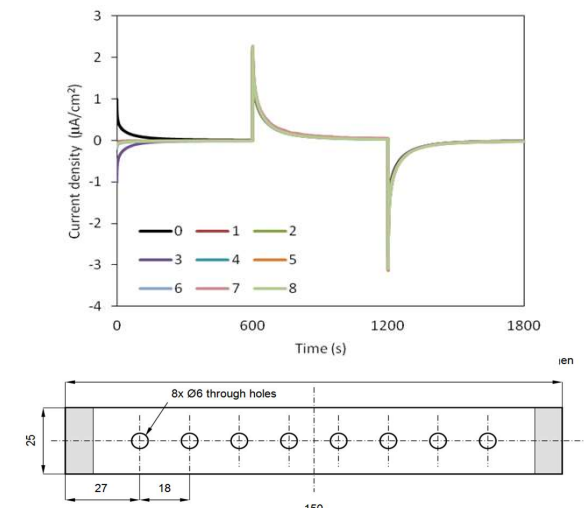
- Range of in-service requirement and conditions to which structural power materials could be exposed, and would be required to tolerate.
- These include
 - ⇒ Cycling (both mechanical and electrical)
 - ⇒ Temperature extremes,
 - ⇒ Fire resistance
 - ⇒ Machining/Finishing
 - ⇒ Impact and Damage Tolerance.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



Local heating following penetrative impact



Cyclic performance



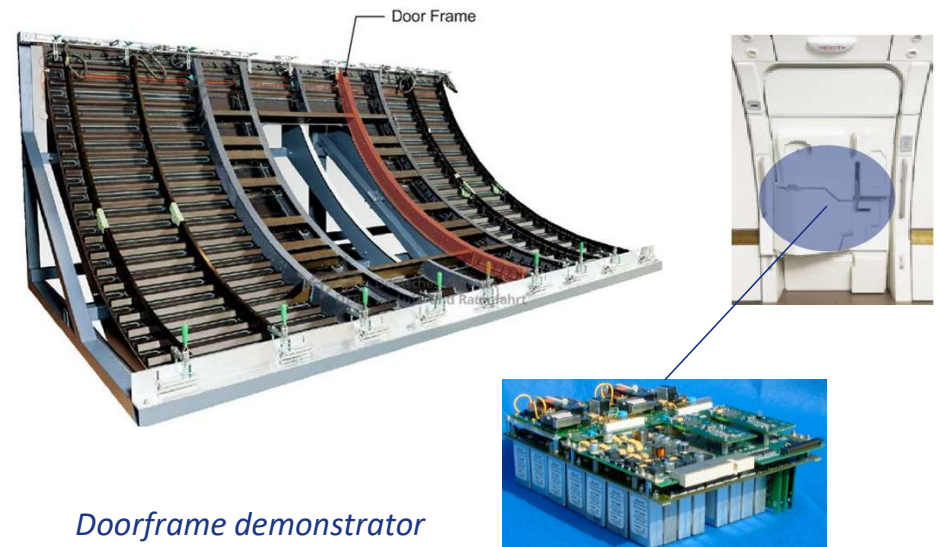
Drilling damage

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*
 - ⇒ *Fabrication*
 - ⇒ *Encapsulation*
 - ⇒ *Current Collection / Scale-up*
 - ⇒ *Multifunctional Material Design*
 - ⇒ *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 a 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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- *Collaborators* - University of Durham, University of Bristol, KTH (Sweden), Chalmers (Sweden), IMDEA (Spain)

