

SORCERER

Structural Power Composites for Future Civil Aircraft

Clean Sky 2 Special Session – AIAA Science & Technology 2021 Forum

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<https://www.sorcerer.eu/>

SORCERER Team

Structural Supercapacitors

Imperial College
London



Milo



Emile



Anthony

Structural Batteries



CHALMERS



Leif

Structural Supercapacitors



Juan

institute
imdea

Structural Power Generation



Dan



KTH
VETENSKAP
OCH KONST

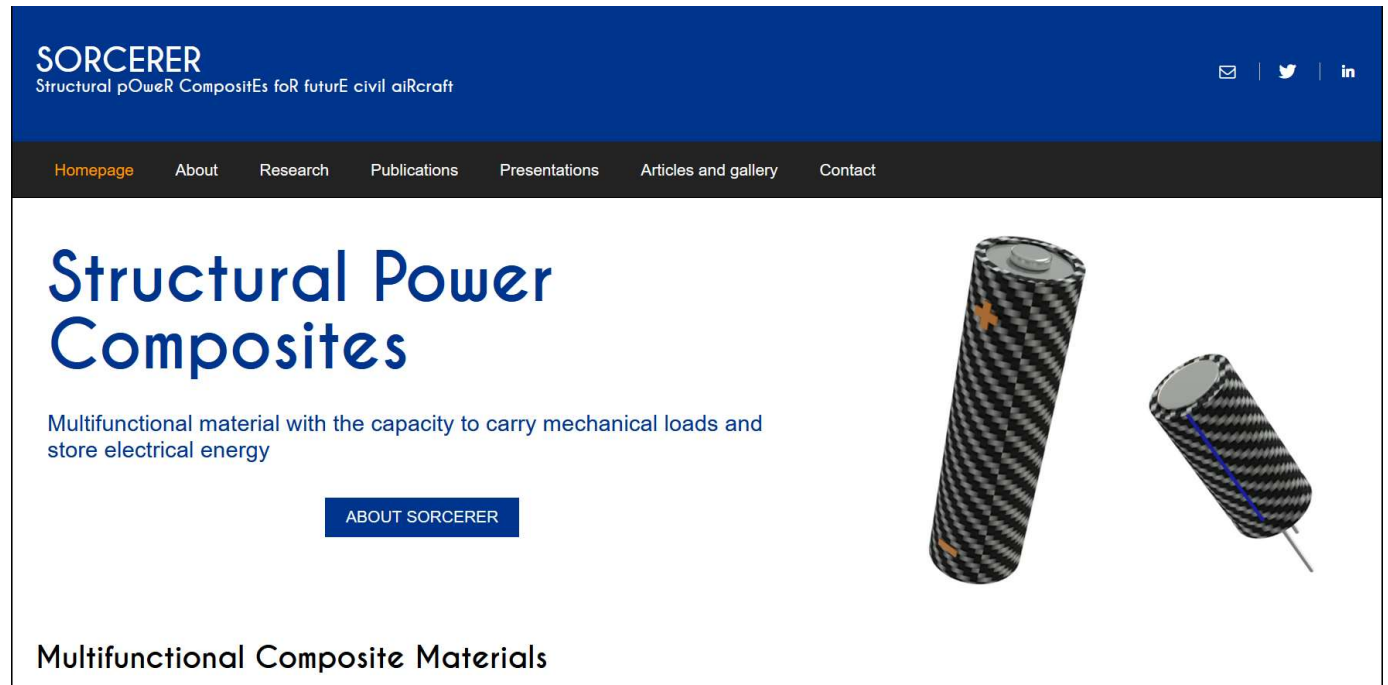


Goran

Aims and Objectives of Presentation

- Introduction to Structural Power
- Overview of SORCERER
- Structural Supercapacitors
- Structural Batteries
- Concluding Remarks

<https://www.sorcerer.eu/>



SORCERER
Structural pOwER CompositEs foR futurE civil aiRcraft

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Structural Power Composites

Multifunctional material with the capacity to carry mechanical loads and store electrical energy

ABOUT SORCERER

Multifunctional Composite Materials

A large stack of green cylindrical batteries, arranged in a grid-like pattern. The batteries are shown from a perspective that makes them appear to recede into the distance. The text "Introduction to Structural Power" is overlaid in the center of the image in a bold, blue, sans-serif font. The background is a plain, light gray surface with a soft shadow cast by the batteries.

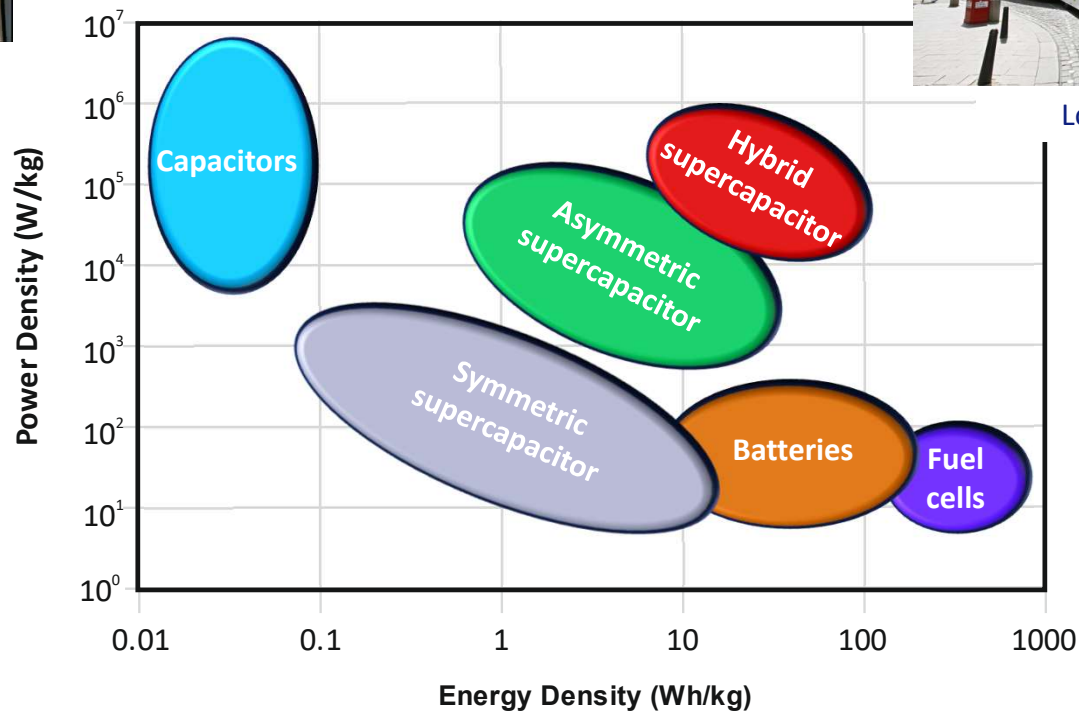
Introduction to Structural Power

Overview of Conventional Energy Storage

Energy weapons



Load-levelling



Portable electronics

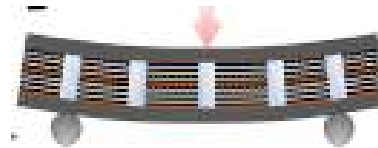
Going beyond Smart Materials....

- Conventional *reductionalist* approach to design - maximise efficiency of individual subcomponents.
 - ⇒ Compartmentalised - 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.

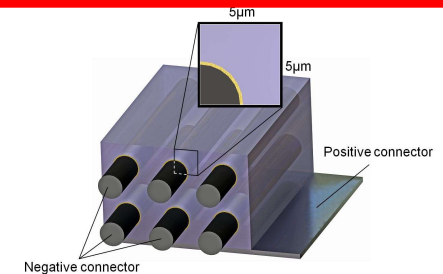
Multifunctional Materials...

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.



T Carlson, PhD Thesis, Luleå University of Technology, Sweden, Sept 2013.

Our Vision for Structural Power



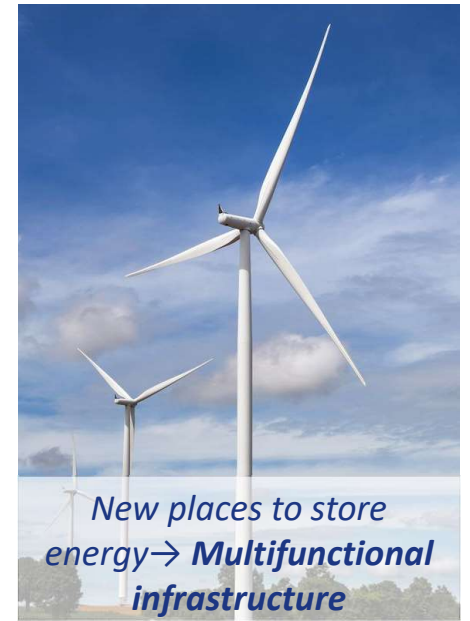
Slender wings → reduced drag and thus greater range



Huge mass & volume reductions → Sustainable transportation



Localisation of power → reduced wiring



New places to store energy → Multifunctional infrastructure



'Slenderisation' → phones as thin as credit cards



Multifunctional structural materials → innovative engineering & design freedom



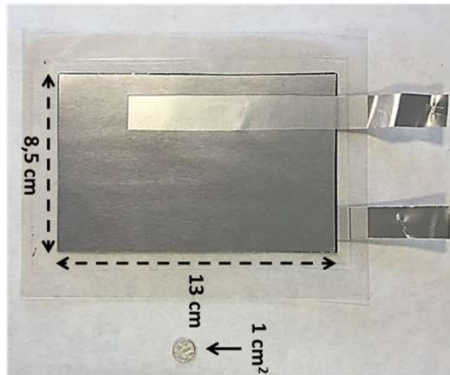
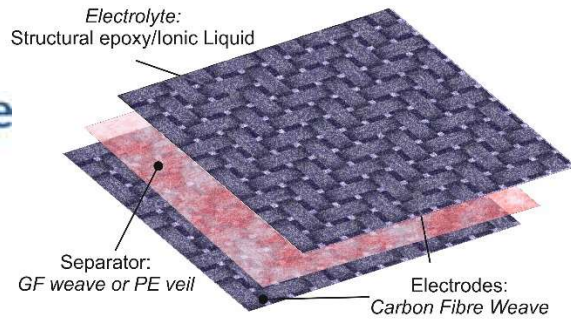
Tailored mass distribution → Innovative drone design



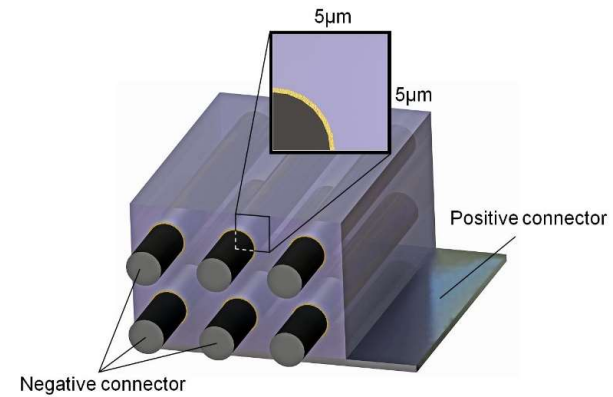
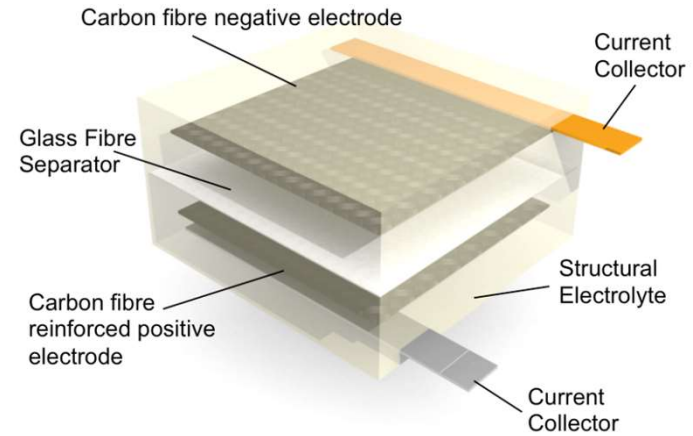
Intrinsic power sources → facilitating sensing, actuation, energy harvesting

Structural Power Concepts

Structural Supercapacitors



Structural Battery



Imperial College London

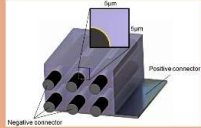
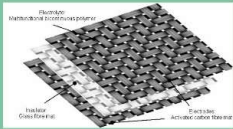
institute
iMdea




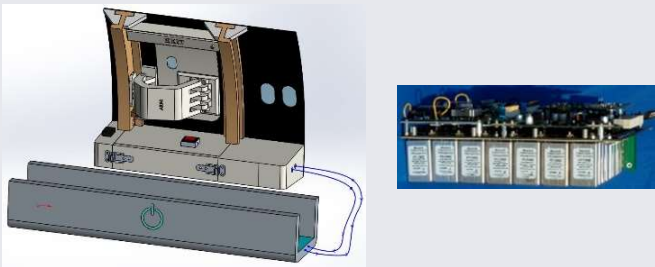



SORCERER Project
(February 2017 – January 2021)

Work Packages in SORCERER

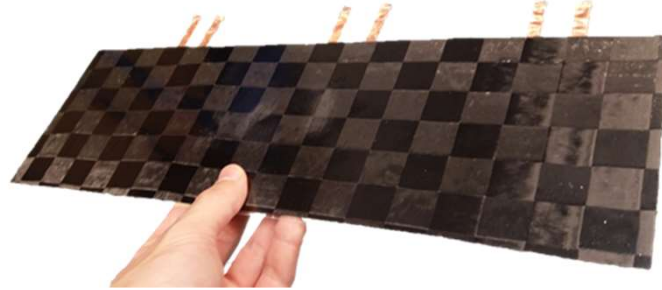
	Technology Improvement	Evaluation	Demonstration
Structural Batteries (Chalmers)	<p>WP1 (Chalmers) <i>Technology Improvement of Battery Function</i></p>		<p>WP5 (Chalmers) <i>Design, Build a Functional Battery Demonstrator</i></p>
Structural Power Generation (KTH)	<p>WP2 (KTH) <i>Technology Improvement of Power Generation Function</i></p>	<p>WP4 (ICL) <i>Evaluation of Structural Behaviour (all devices)</i></p>	<p>WP6 (KTH) <i>Design, Build a Functional Energy Generator Demonstrator</i></p>
Structural Supercapacitors (ICL/IMDEA)	<p>WP3 (ICL) <i>Technology Improvement of Supercapacitor Function</i></p>		<p>WP7 (ICL) <i>Design, Build a Functional Structural Supercapacitor Demonstrator</i></p>

SORCERER Demonstrators

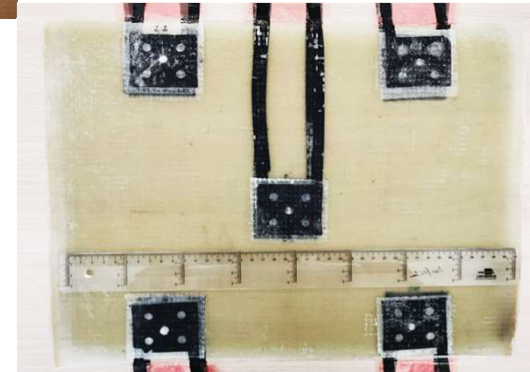
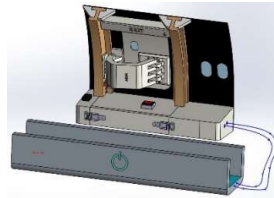
Demo #	Component (Device)	Description	Aircraft Domain & Aims
1	 <p>Representative of PSU (Structural Battery)</p>	<ul style="list-style-type: none"> • Full colour CLEDU with PoD interface. Option for connecting single colour illumination devices without control electronics. A4 laminate representative of the PSU. 	<p>CABIN</p> <ul style="list-style-type: none"> • 28Volts DC • Integrated battery (reading lights) • Characterise functionality. • Tentative business case compilation, including simplified power cable installation.
2	 <p>DEPS (Structural Supercapacitor)</p>	<ul style="list-style-type: none"> • Back-up power system the 16 A380 passenger doors. • Required moment: 800-900 Nm • Input power: 130VA @ 28VDC • DC Output: 60A and 6A • 400 x 230 x 140mm (4.2kg) 	<p>SYSTEM</p> <ul style="list-style-type: none"> • Integrated structural supercapacitor in CFRP door structure. • Demonstrate for 'comfort opening' of Door for operation of electric door opening motor. • Characterise structural behaviour and functionality.
3	 <p>MRP (Structural Supercapacitor)</p>	<ul style="list-style-type: none"> • Controller to deal with short power drop (200ms). Fabricated box from structural supercapacitor 	<p>SYSTEM</p> <ul style="list-style-type: none"> • Integrated structural supercapacitor in systems box structure.

SORCERER Demonstrators Delivered

Structural Battery



CHALMERS




institute
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Imperial College
London

Structural Supercapacitors

Structural Supercapacitor

A roll of dark, woven carbon fiber material is shown in a laboratory setting. The material is tightly wound and has a distinct diagonal weave pattern. It is held in place by a metal bracket on the left. In the background, there are various pieces of laboratory equipment, including pipes and a control panel. The text "Structural Supercapacitors: Imperial College London & IMDEA Materials" is overlaid in a semi-transparent box in the center of the image. The text is in a bold, blue, sans-serif font. The background is slightly blurred, focusing attention on the material and the text.

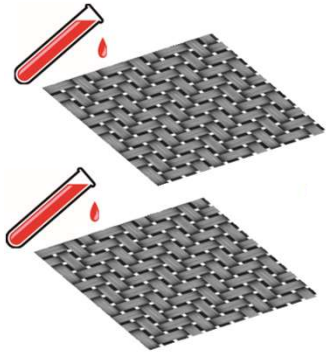
**Structural Supercapacitors:
Imperial College London &
IMDEA Materials**

Loss Energy

Department of
Materials

Department of
Chemistry

SORCERER Device Fabrication and Assembly



(a)

- (a) Infuse individual CF lamina with CAG precursor and then age;
- (b) Pyrolyse individual lamina to form the CF/CAG;
- (c) Attach current collectors;
- (d) Prepreg separator with multifunctional matrix;
- (e) Assemble device to produce CF/Sep/CF laminate;
- (f) Infuse laminate with ionic liquid;
- (g) Encapsulate device in insulating, structural composite.

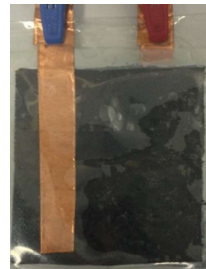
Imperial semi-structural & MF cell performance

Type	Electrodes	Separator	Electrolyte	C (F)	m (g)	V (V)	ESR (Ω)	C* (F/g)	E* (Wh/kg)	P* (kW/kg)
Semi-structural	CAG CF 43 gsm	PET/ceramic (23 μ m)	EMI-TFSI	1.01	0.36	2.7	1.49	3.1	3.2	3.4
Structural	CAG CF 43 gsm	PET/ceramic (23 μ m)	MF (40%)	0.51	0.36	2.7	4.80	1.4	1.4	1.1
Conventional	Maxwell BCAP0150 ¹ , length = 50 mm, dia. = 25 mm			150	32	2.7	14 m Ω	4.7	4.7	4.1

$$E_{\max} = \frac{\frac{1}{2} CV^2}{3,600 \times \text{mass}}$$

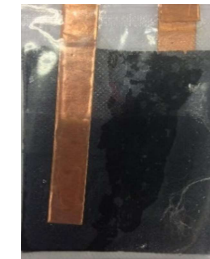
$$P_{\max} = \frac{V^2}{4 \times \text{ESR}_{\text{DC}} \times \text{mass}}$$

¹ Maxwell BCAP0150 datasheet



*Normalised to active mass

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

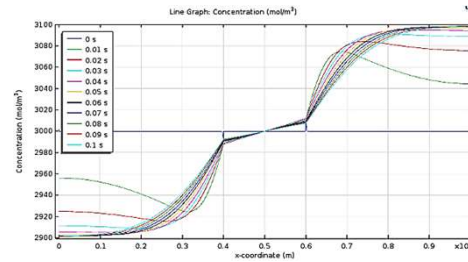
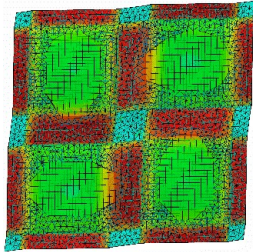


Aspiration:

E* = 2 Wh/kg

P* = 1 kW/kg

Imperial Multifunctional Modelling and Design



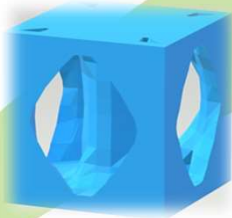
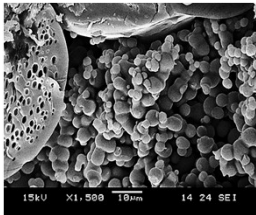
Mesoscale multi-physics modelling

Prediction of mechanical and electrochemical behaviour and interactions at device level.



Macroscale multifunctional design

Methodologies to determine how best to tailor and design multifunctional materials and systems.



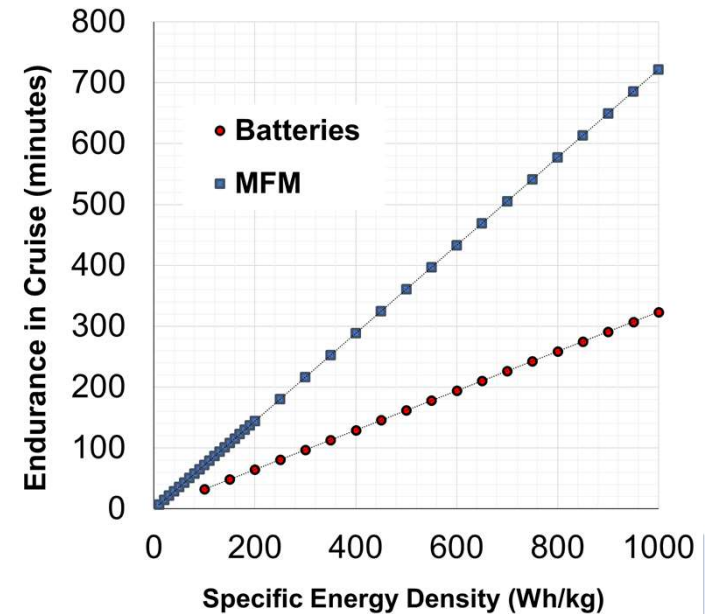
Microscale material optimisation

Topology optimisation of constituent materials to maximize multifunctional properties.



Multifunctional Design

- *How do we design multifunctional platforms, and compare their performance to that of the conventional equivalent systems?*
- 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.
- 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.



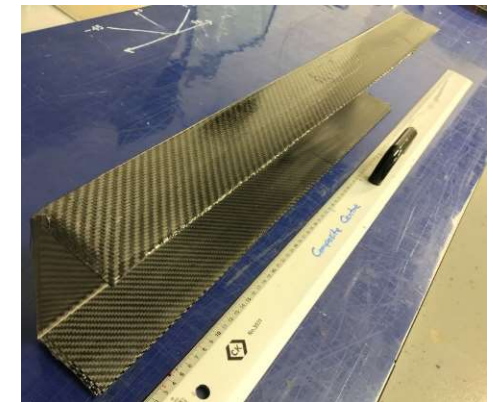
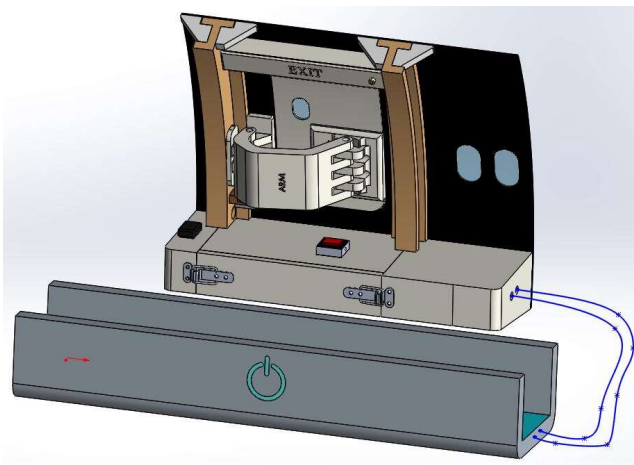
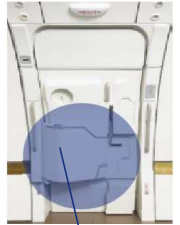
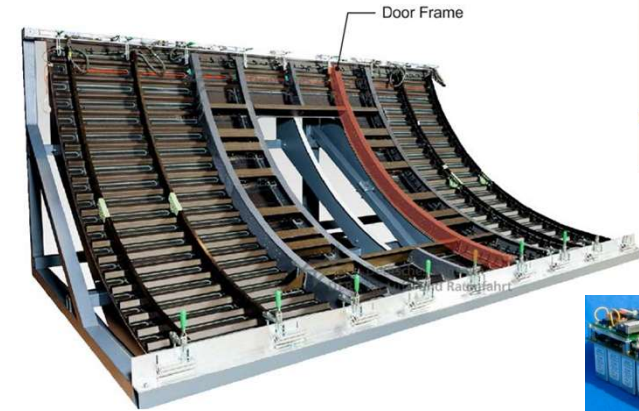
Imperial SORCERER Demonstrator

Manufacture has been delayed by Covid and social distancing constraints

Door assembly now complete.

C-beam demonstrator - issues hindered completion:

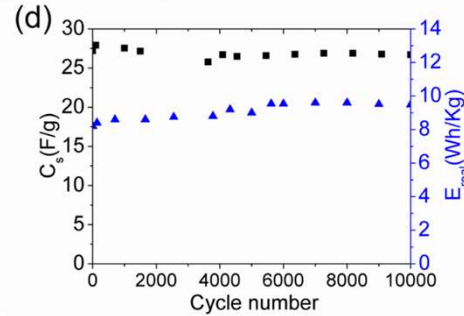
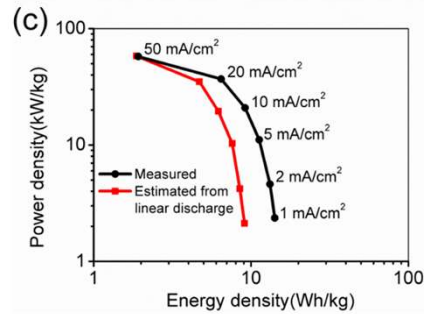
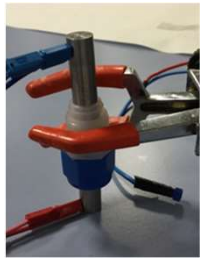
- **Scale-up** – repeatability issues with making multiple cells;
- **Current collection** – adhesive interacts with IL, causing loss in performance;
- **Encapsulation** – issues with leakage;



C-Beam and single cell

IMDEA – from nanostructured materials to structural devices

Materials synthesis and study

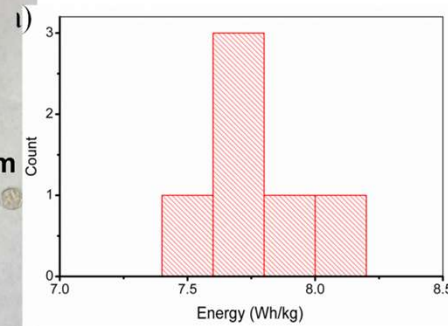
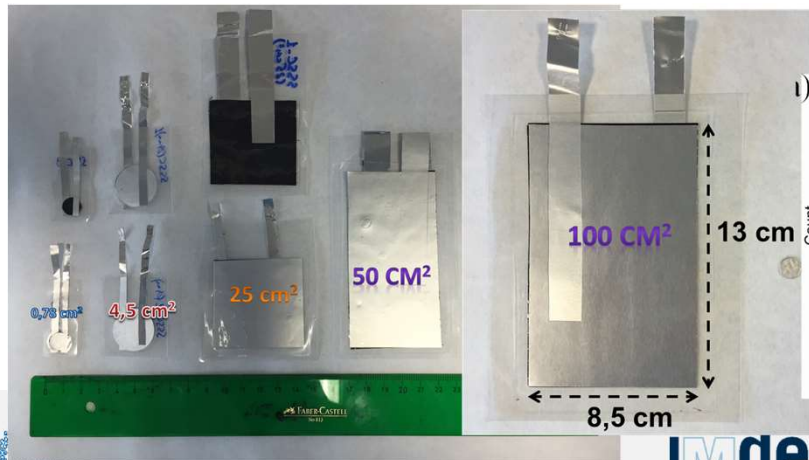


Development of assembly route

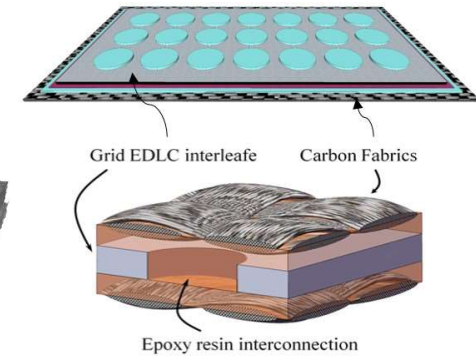
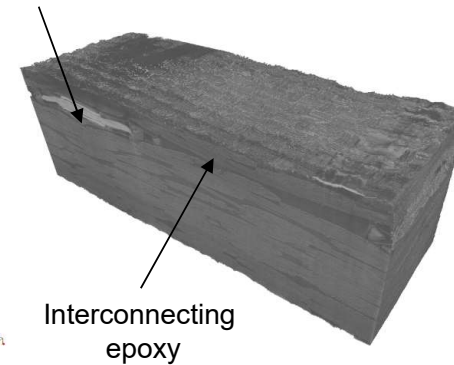


Senokos et al, Adv. Mater. Technol. 2017 1600290

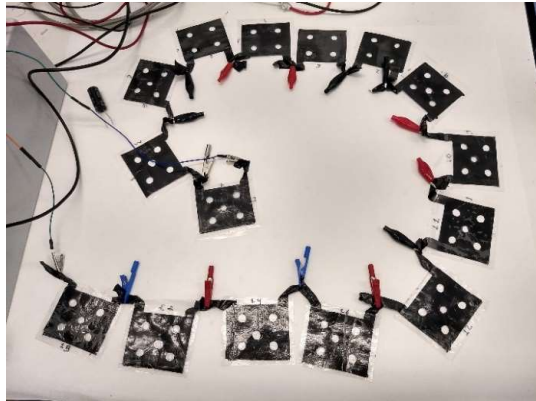
Reproducibility and device fabrication



Supercapacitor interleaf



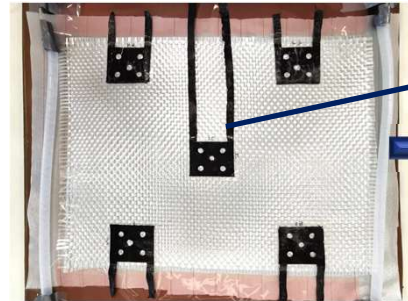
IMDEA – Fabrication of demonstrator



Fabrication



Assembly with glass fiber layers



Externally connected CNT tape

Resin infusion

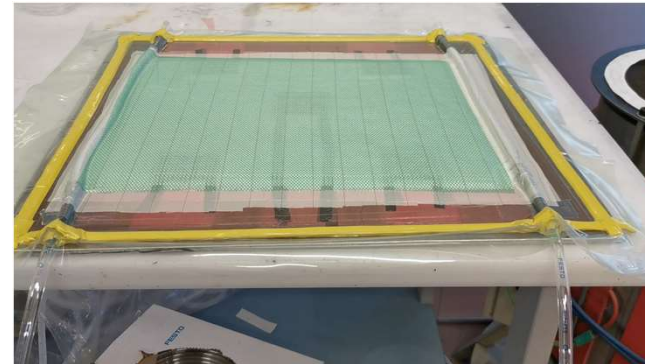


Structural Supercapacitor

Dimension (40x 25 cm²)



After curing



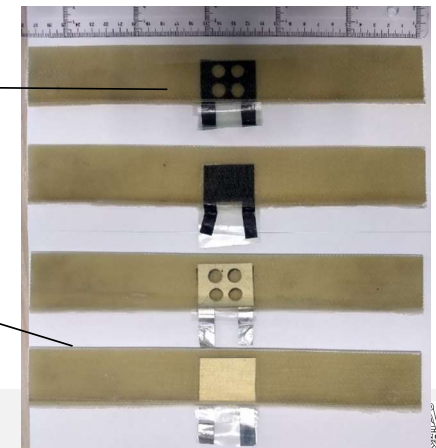
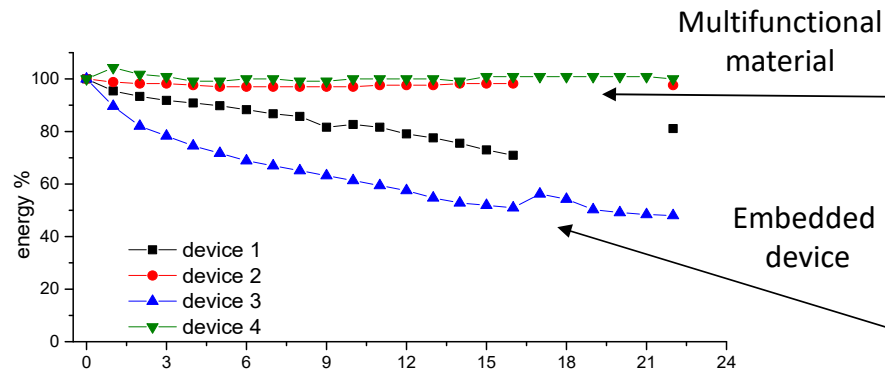
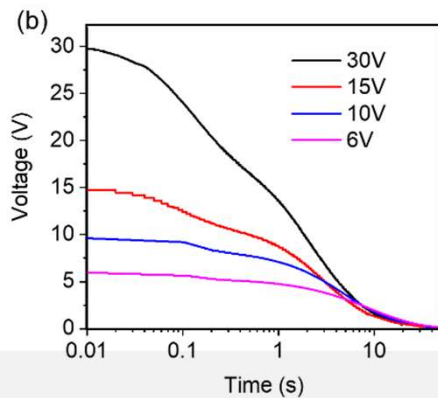
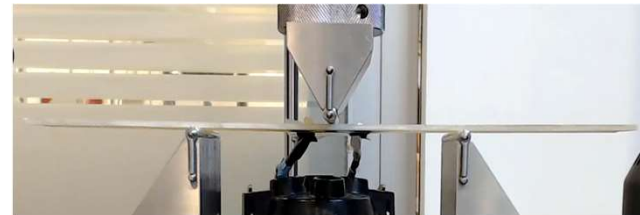
IMDEA – Structural supercapacitor as energy buffer

Use of structural supercapacitor as energy buffer for local DC power supply according to specifications provided by Airbus (power supply for 20 ms)

Structural supercapacitor

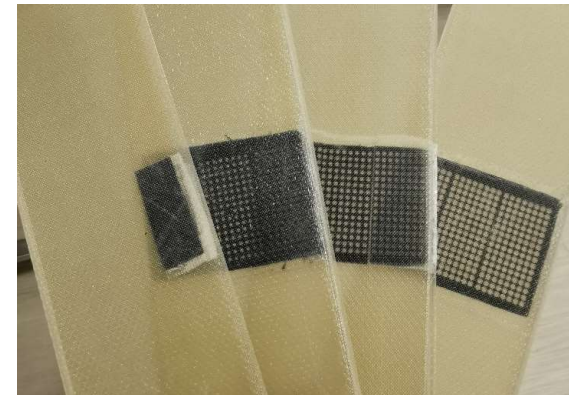
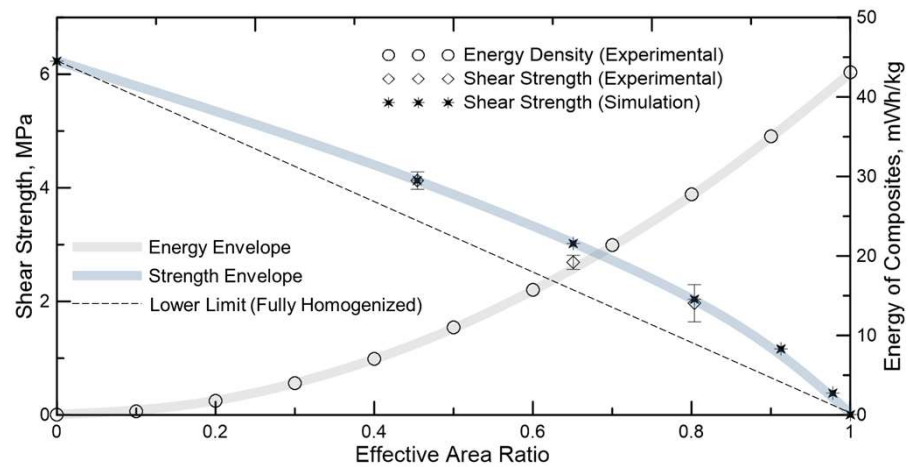
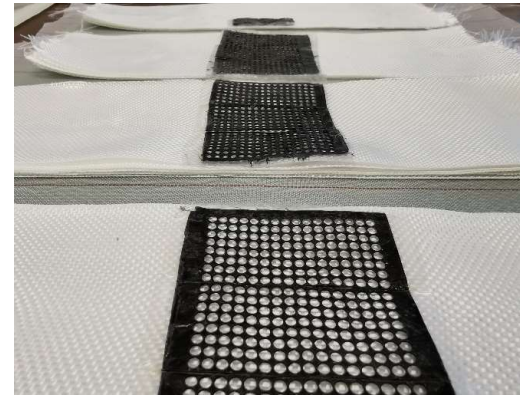
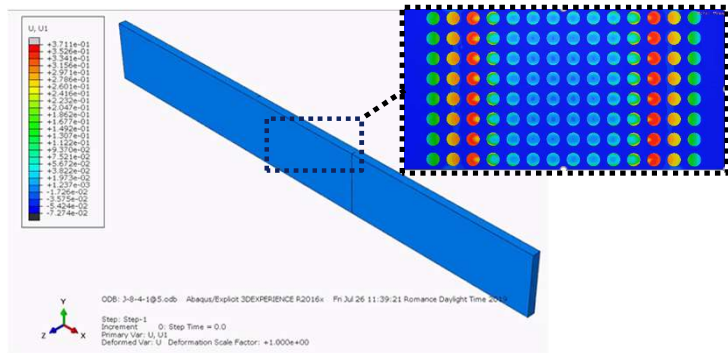


The use of nanostructured current collectors is critical to ensure durability of these structural power composites



IMDEA – Multifunctional property envelope

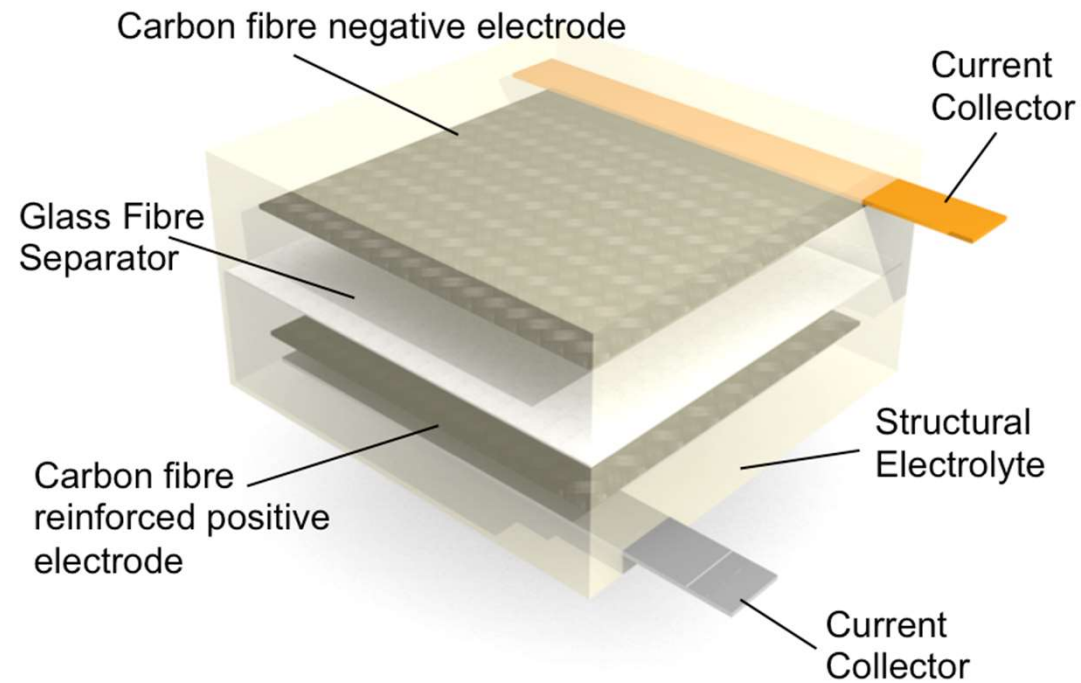
Design and fabrication of laminated structural power composite with adjustable structural/power balance





Structural Batteries: Chalmers & KTH

The laminated structural battery



Asp et al. *Funct. Comp. Struct.* 1, 2019, 042001



CHALMERS



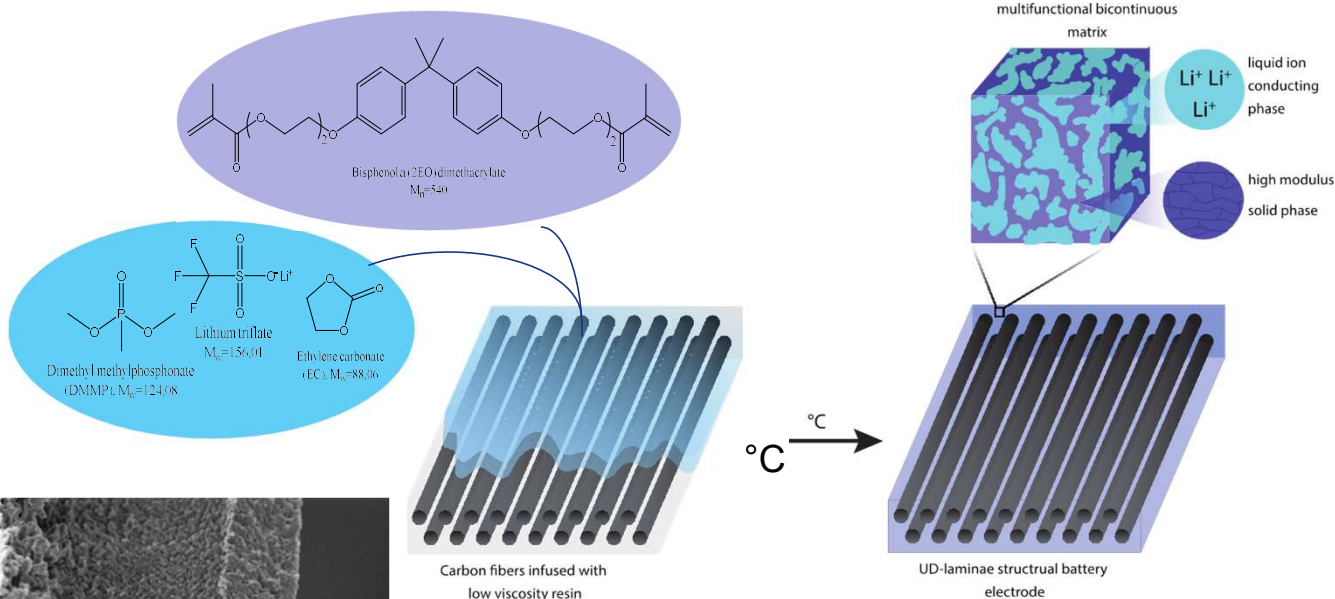
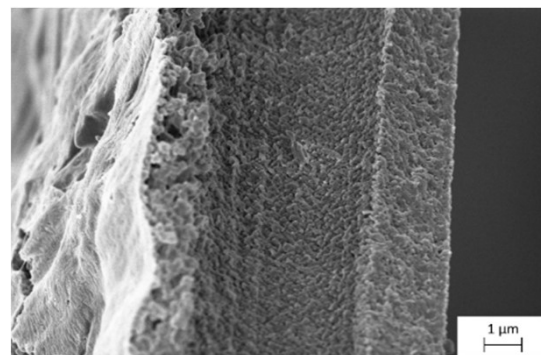
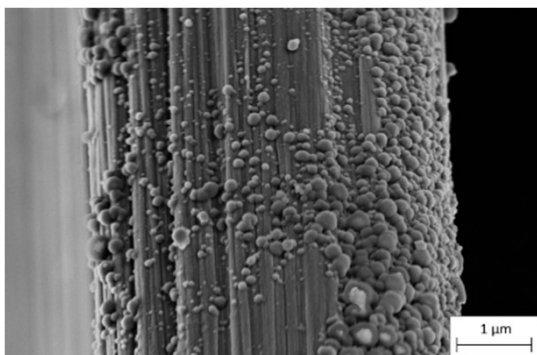
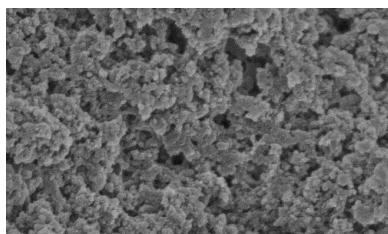
CHALMERS

Structural battery electrolyte

Monomer Electrolyte

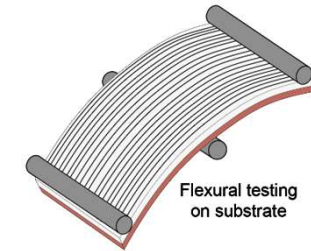
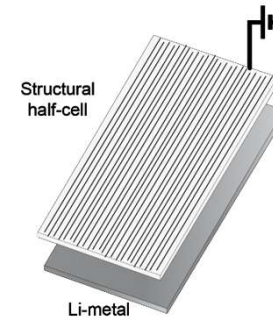
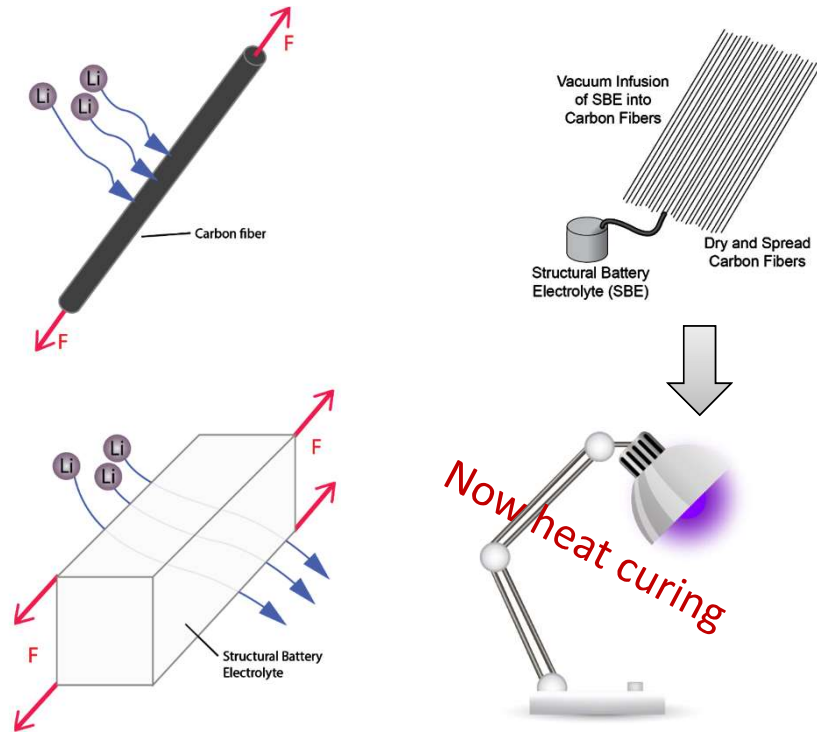


non-polar polar

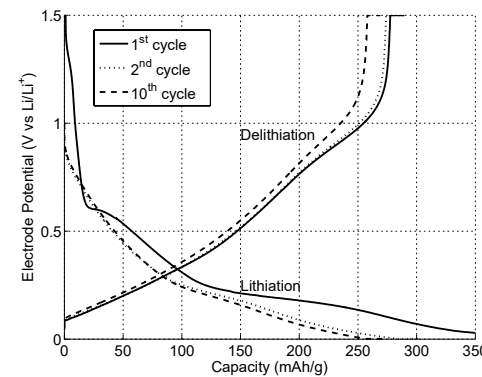


Schneider L, Ihrner N, Zenkert D, Johansson M., *ACS Appl Ener Mater*, 2, 2019
Ihrner et al, *J.Mat.Chem.A.*, 5, 2017

Negative carbon fibre electrode



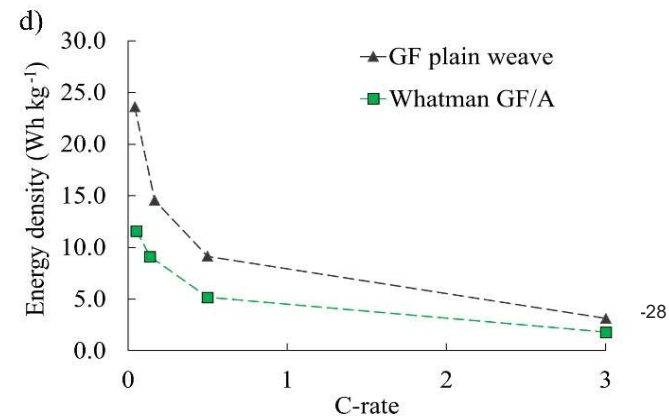
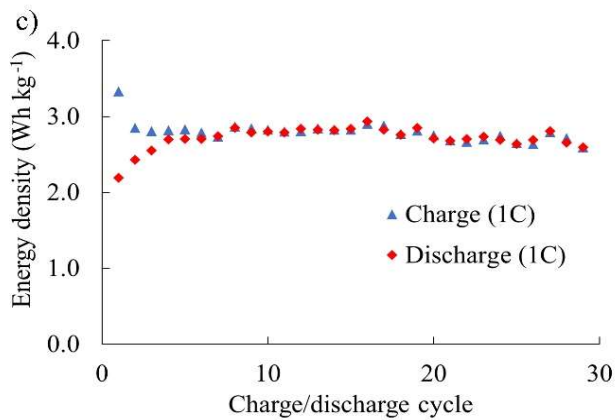
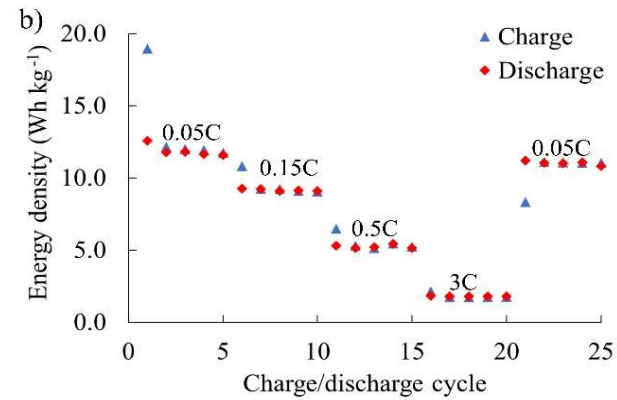
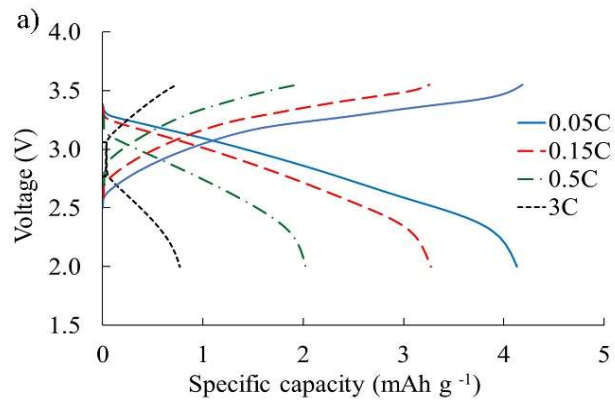
Electrochemical
Cycling efficiently
Capacity \approx 230 mAh/g



Mechanical (lamina data)
 $E_1 \approx$ 52 GPa (now > 100 GPa)
 $E_2 \approx$ 1.7 GPa
 $G_{12} \approx$ 1.5 GPa
 $\sigma_1 \approx$ 1000 MPa
 $\sigma_2 \approx$ 12 MPa
 $\tau_{12} \approx$ 13 MPa

Johannisson *et al*, *Compos. Sci. Technol.*, 168, 2018

Electrochemical performance

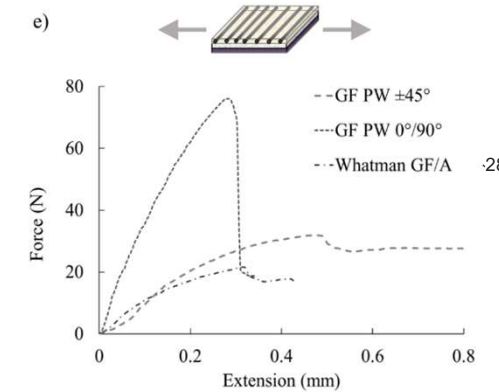
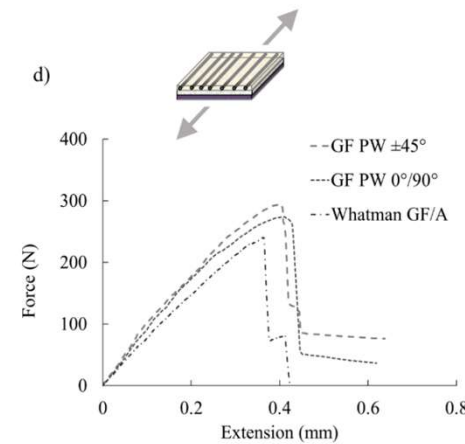
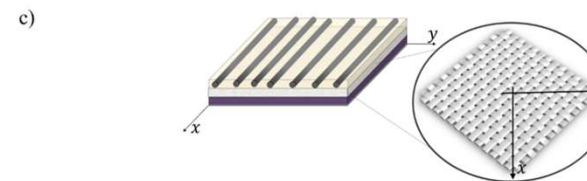
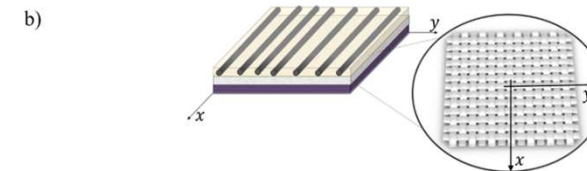
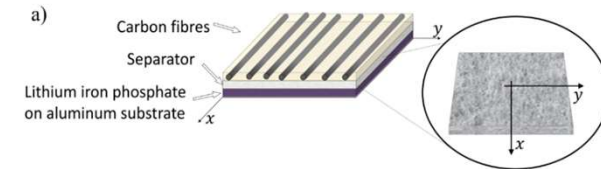


Asp LE, et al. *Adv. Energy Sustainability Res.* DOI: [10.1002/aesr.202000093](https://doi.org/10.1002/aesr.202000093)

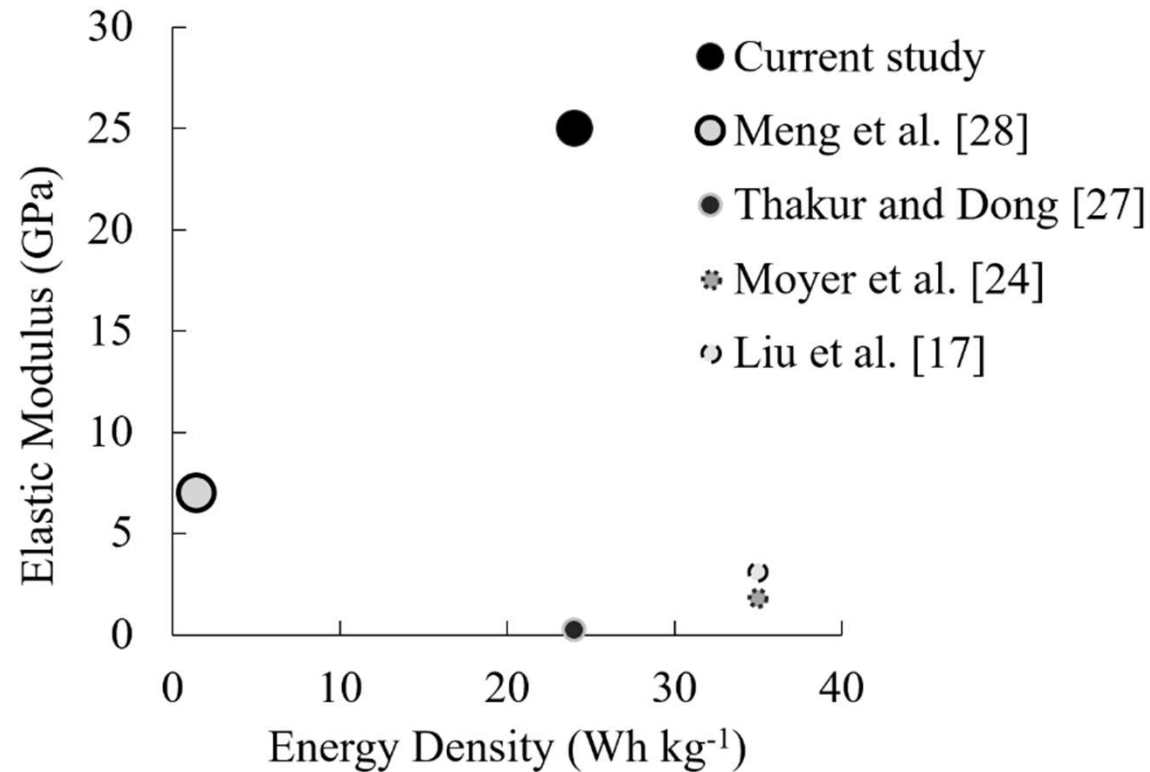
Mechanical performance

Property	Separator type		
	Whatman GF/A	GF plain weave $\pm 45^\circ$	GF plain weave $0^\circ/90^\circ$
E_x [GPa]	18.3 (± 0.9)	14.6 (± 0.6)	25.4 (± 3.3)
E_y [GPa]	2.9 (± 0.5)	2.8 (± 0.2)	13.3 (± 0.7)
X [MPa]	> 163	> 312	> 287
Y [MPa]	> 16	> 34	> 72

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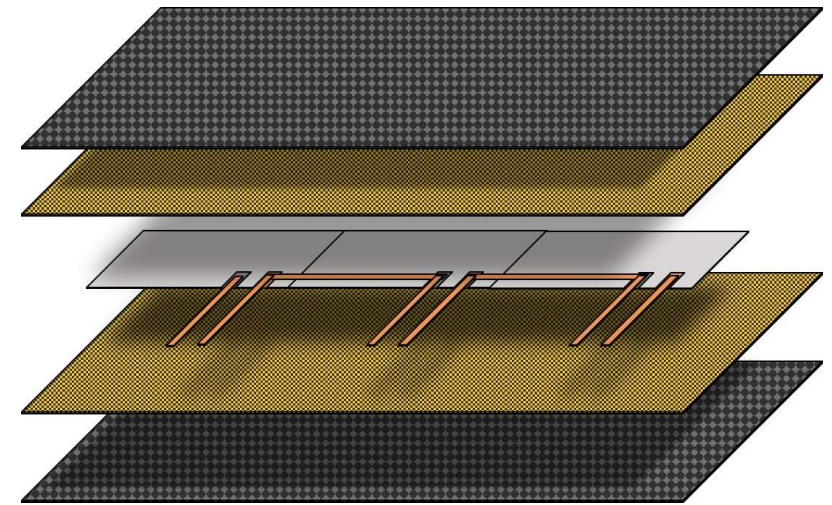
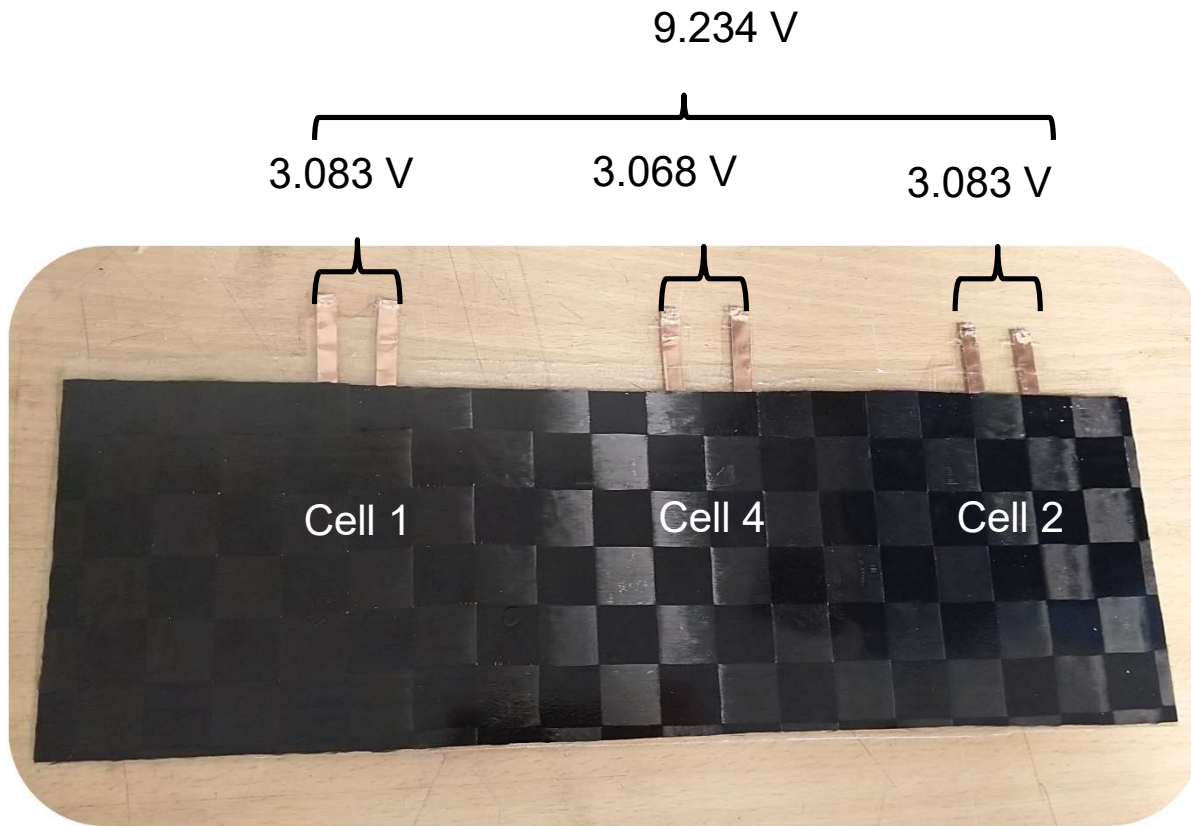


Multifunctional performance



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SORCERER structural battery demonstrator



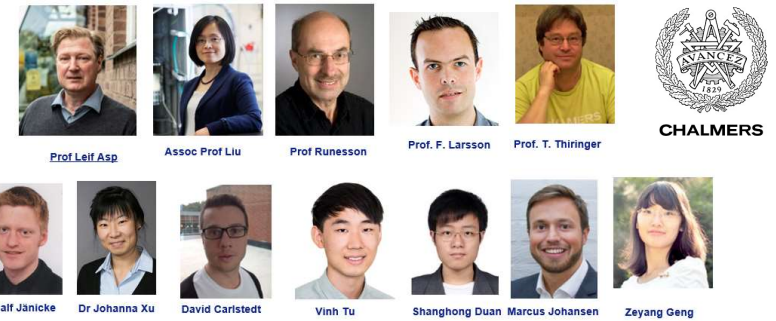
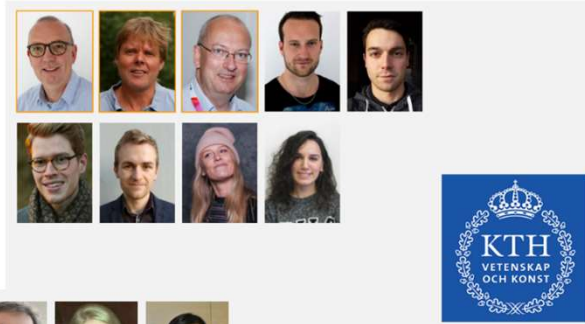
Multichannel testing of the three encapsulated cells in series

<https://doi.org/10.1002/aesr.202000093>

Key Achievements and Concluding Remarks

- **Structural Batteries:**
 - Carbon fibre based positive electrodes with good electrochemical capacity;
 - Developed a new structural battery electrolyte which permits infusion manufacturing and heat curing with good multifunctional performance;
 - Demonstrated a structural battery with unprecedented multifunctional properties: first multi-cell structural battery component;
- **Structural Supercapacitors:**
 - Demonstrated a device performance of 1.4 Wh/kg and 1.1 kW/kg, the latter in excess of the original target;
 - Scaled-up CAG development, demonstrated pseudocapacitance and methodologies for making non-flat CAG components;
 - Scalable route to manufacture all-solid, laminated supercapacitor composites and demonstrated electrical demonstrator.
- **General Structural Power:**
 - The consortium developed suite of structural power modelling tools and design methodologies which will ultimately facilitate both future materials design and certification of structural power devices;
 - Demonstrated methodologies for current collection and encapsulation of structural power devices.
- **The SORCERER consortium has pioneered structural power & are trailblazing this emerging technology.**

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