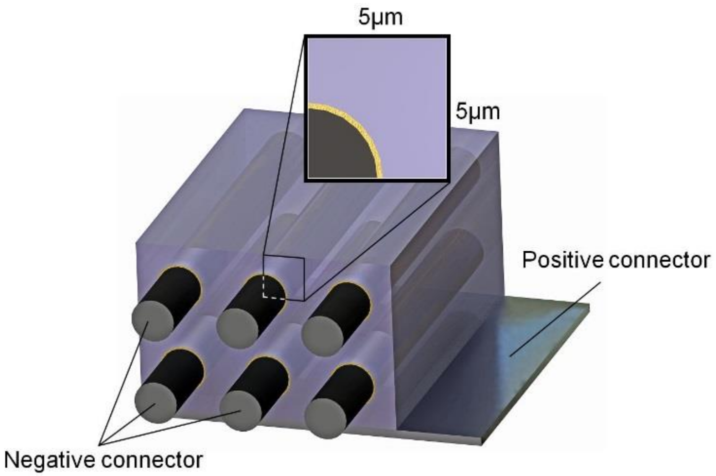

Damage Tolerance and Durability of Structural Power Composites

Space Power Workshop, Arlington VA, May 2017

Prof Emile S. Greenhalgh[*] & Prof Leif Asp[‡],
Prof Milo Shaffer[*], Prof Anthony Kucernak[*], Dr Koon-Yang Lee[*]
Prof Dan Zenkert[†], Prof Goran Lindbergh[†], Niklas Ihrer [†]

[*]Imperial College London; [†]KTH Sweden; [‡]Chalmers Sweden

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Overview of Research Team and Motivation

Structural Power Team

Structural Supercapacitors

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Milo

Emile

Koon-Yang

Anthony

Structural Batteries

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Leif

KTH VETENSKAP OCH KONST

Dan

Goran

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Current Research Portfolio £5.5M (~$7M)

Fundamentals
EPSRC – Beyond Structural (ICL)
Swedish Research Council
(Chalmers/KTH)

Fabrication/Scale-up
Composite
Manufacturing Hub (ICL)
Swedish Energy Agency
(Chalmers/KTH)

Structural Power Composites

Mechanical/Durability
Damage Tolerance &
Durability of SPCs (all)
Swedish Energy Agency
(Chalmers/KTH)

Applications
Clean Sky 2 (EU) – SORCERER (All)

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International Leadership

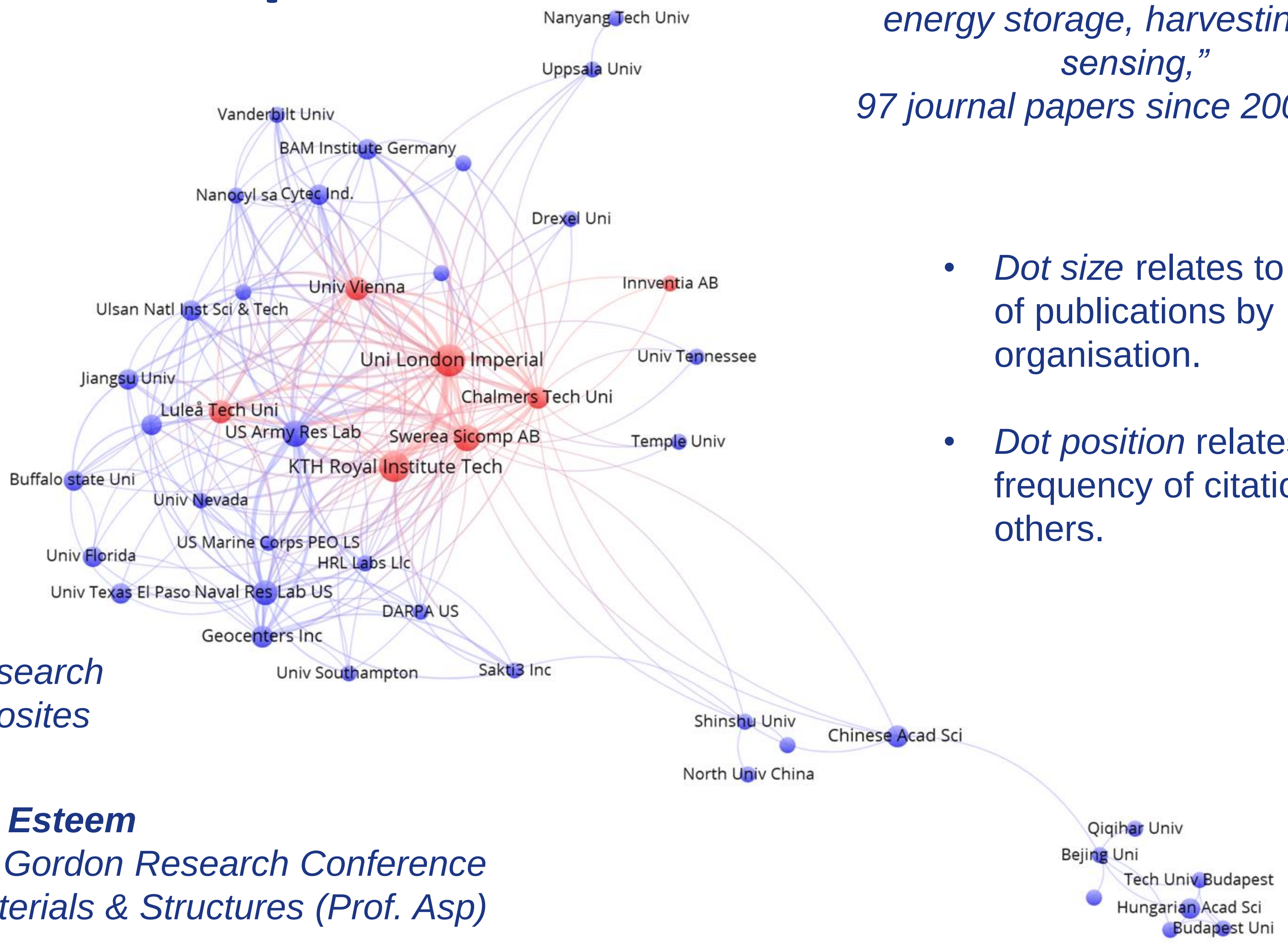
"Multifunctional composite materials for energy storage, harvesting and sensing,"
97 journal papers since 2000 WoS

Central
in research field

First
- led first research campaigns on structural power in Europe (Prof. Greenhalgh)

Largest
- leads World's largest on-going research project on structural battery composites (Prof. Lindbergh)

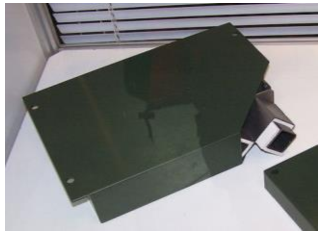
Esteem
Invited speaker: First Gordon Research Conference on Multifunctional Materials & Structures (Prof. Asp)



- *Dot size* relates to number of publications by organisation.
- *Dot position* relates to frequency of citation by others.

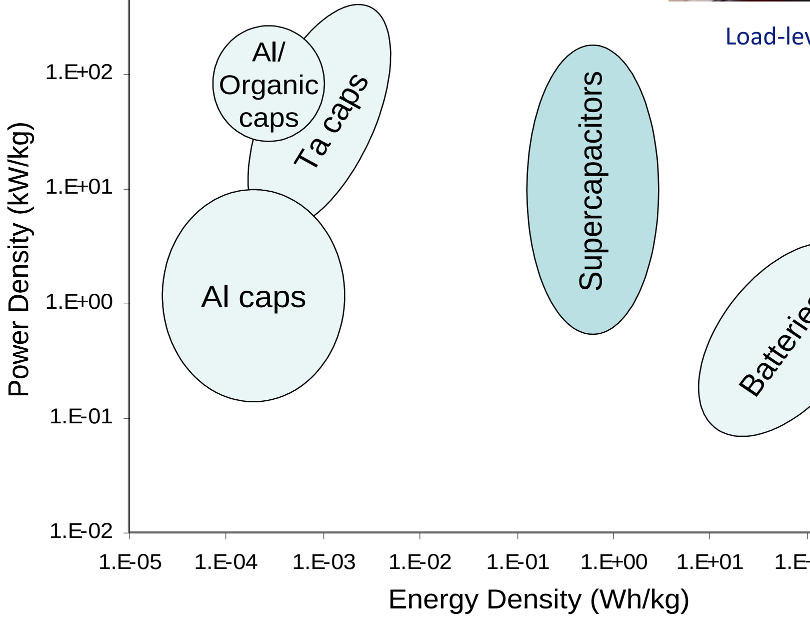
Motivation – 'Massless Energy'

- Conventional *reductionalist* design approach - maximise efficiency of individual subcomponents.
  - ⇒ Difficult compromises;
  - ⇒ Limiting technological advance and stifling innovative design.
- Different *holistic* approach; materials which simultaneously perform more than one function.
  - ⇒ **Simultaneously carry high mechanical loads whilst storing/delivering electrical energy.**
- Carbon fibres are attractive
  - ⇒ commonly used as both electrodes and structural reinforcements.



Reactive armour

Load-levelling



Portable electronics

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Beyond Smart Materials....

Smart Materials (Multifunctional Structures) *–*

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

➢ e.g. embedding miniature or shaped sensors or actuators within structural materials

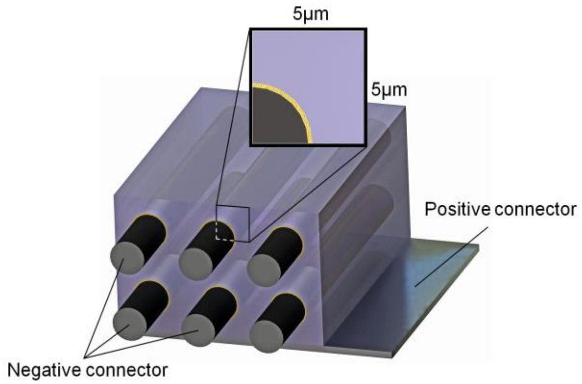
J. P. Thomas & M. A. Qidwai. "The design & application of multifunctional structure-battery materials systems." JOM. v57 p18-24. 2005.

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

➢ **Emerging, highly interdisciplinary field**



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

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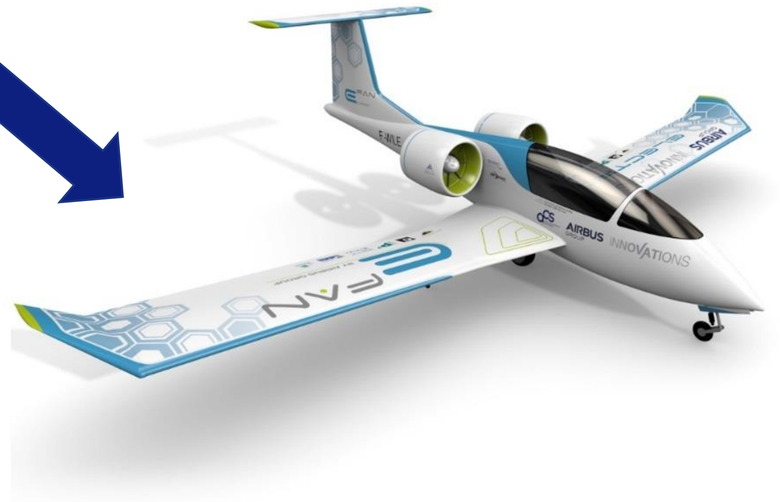
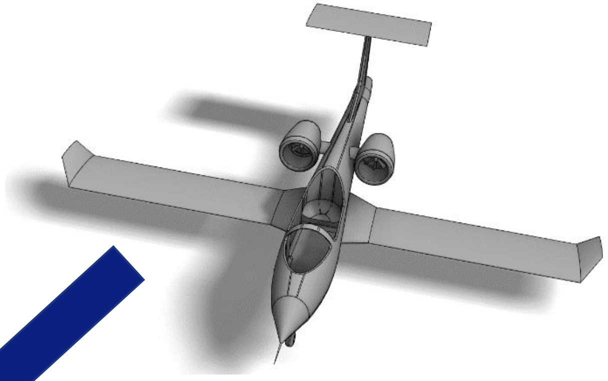
Motivation – Example (E-Fan)

167kg Battery

$\Omega_s = 0$
$\Omega_E = 1$

E-Fan 1.0 (500kg)





Structure/Systems

$\Omega_s = 1$
$\Omega_E = 0$

Ω_s = 0, Standard power source does not have any structural capabilities
Ω_E = 0, Standard structure, which has no electrical energy storage

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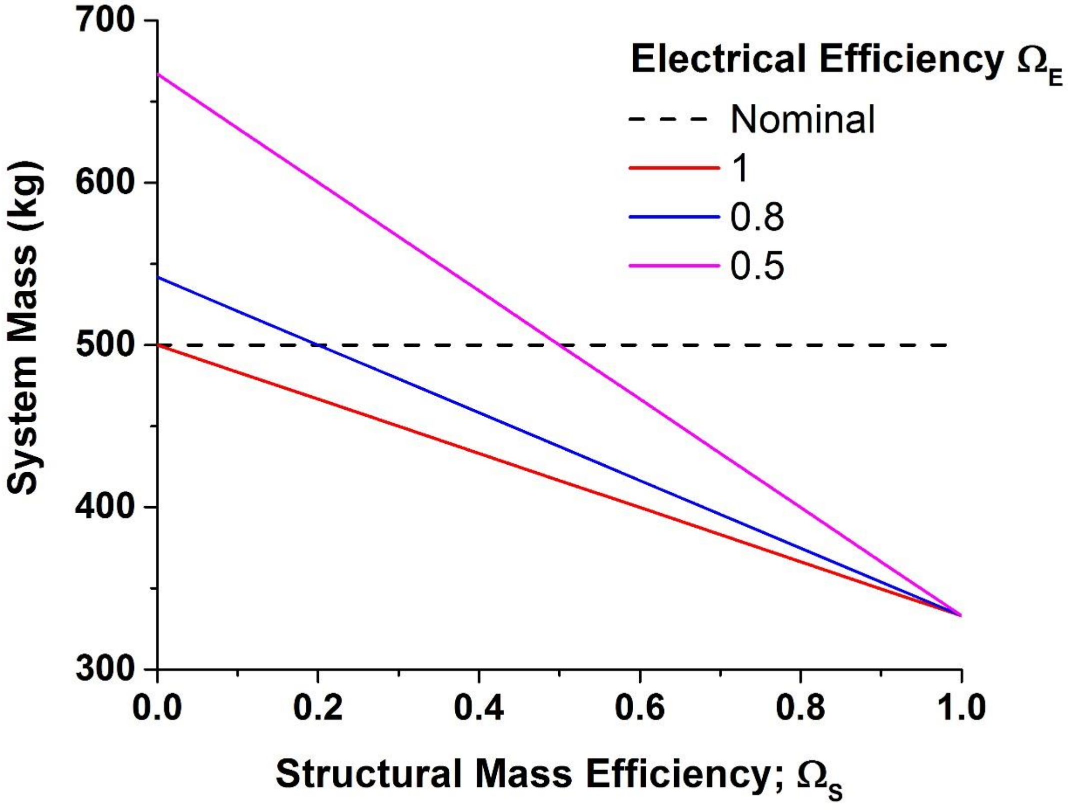
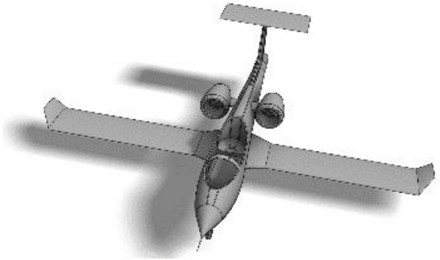
Motivation – Example (E-fan)





$\Omega_s = 0$
$\Omega_E = 1$

$\Omega_s = 1$
$\Omega_E = 0$

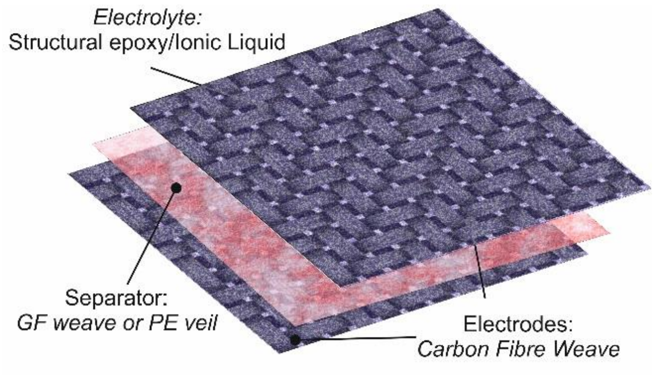
Structural Power Material

$\Omega_s = ?$
$\Omega_E = ?$

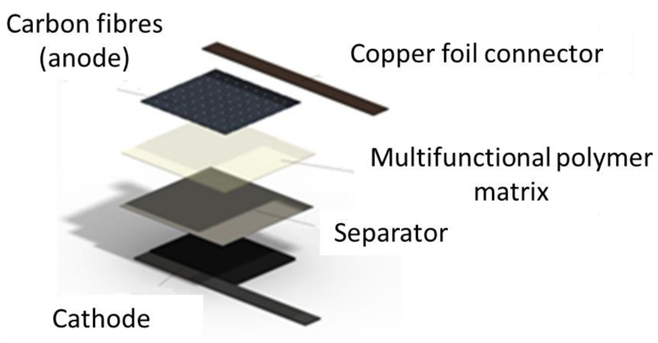
$$\Omega_E + \Omega_S > 1$$

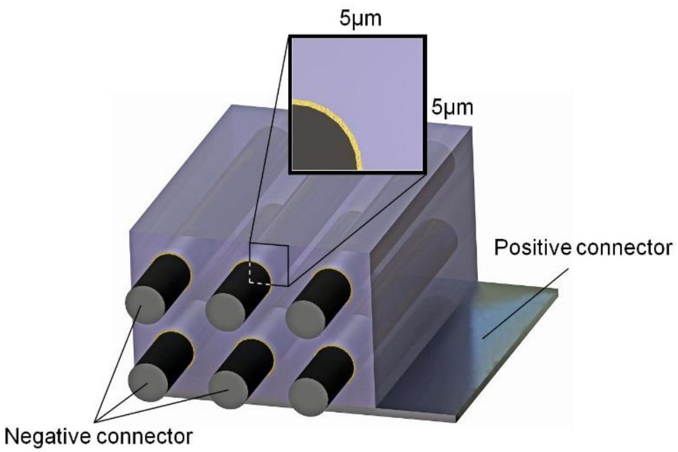
Concepts for Structural Power

Structural Supercapacitor (ICL)



Structural Battery (Chalmers/KTH)





➢ ***Methodology – adopt <u>structural</u> material and imbue with electrochemical functionality***

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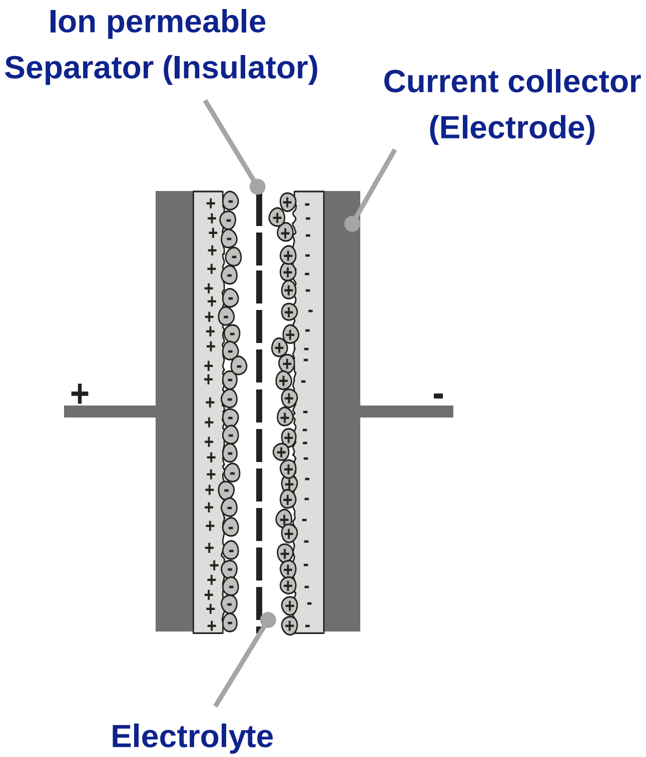
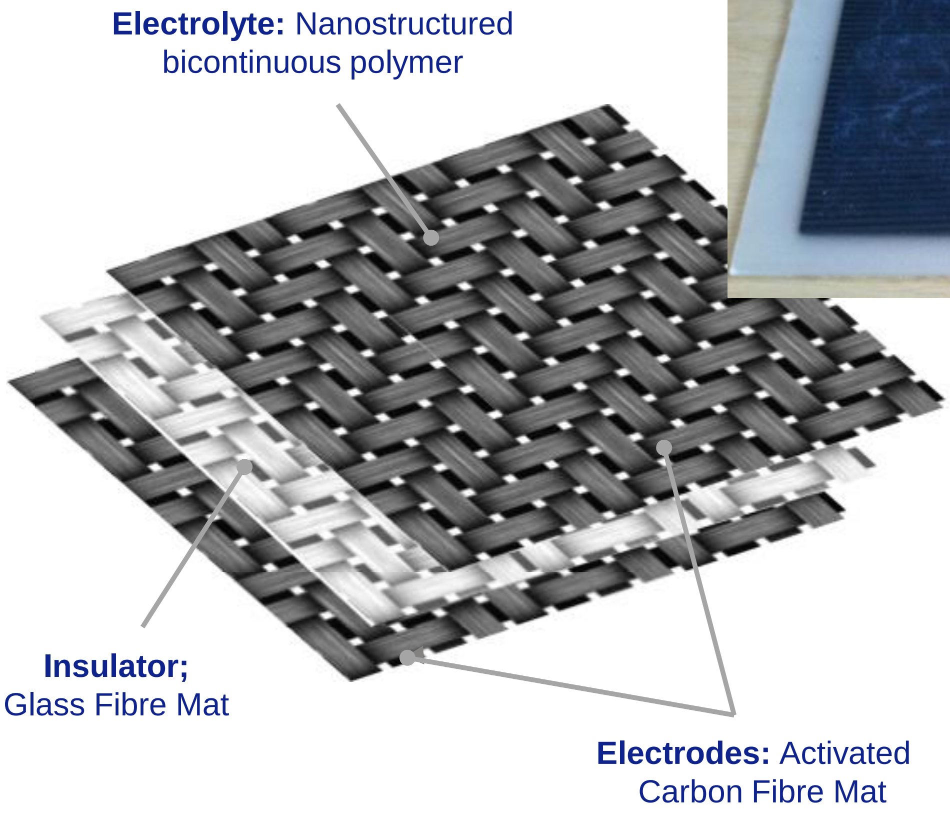
Structural Supercapacitors

ICL

Supercapacitor Device





Conventional Supercapacitor

Structural Supercapacitor

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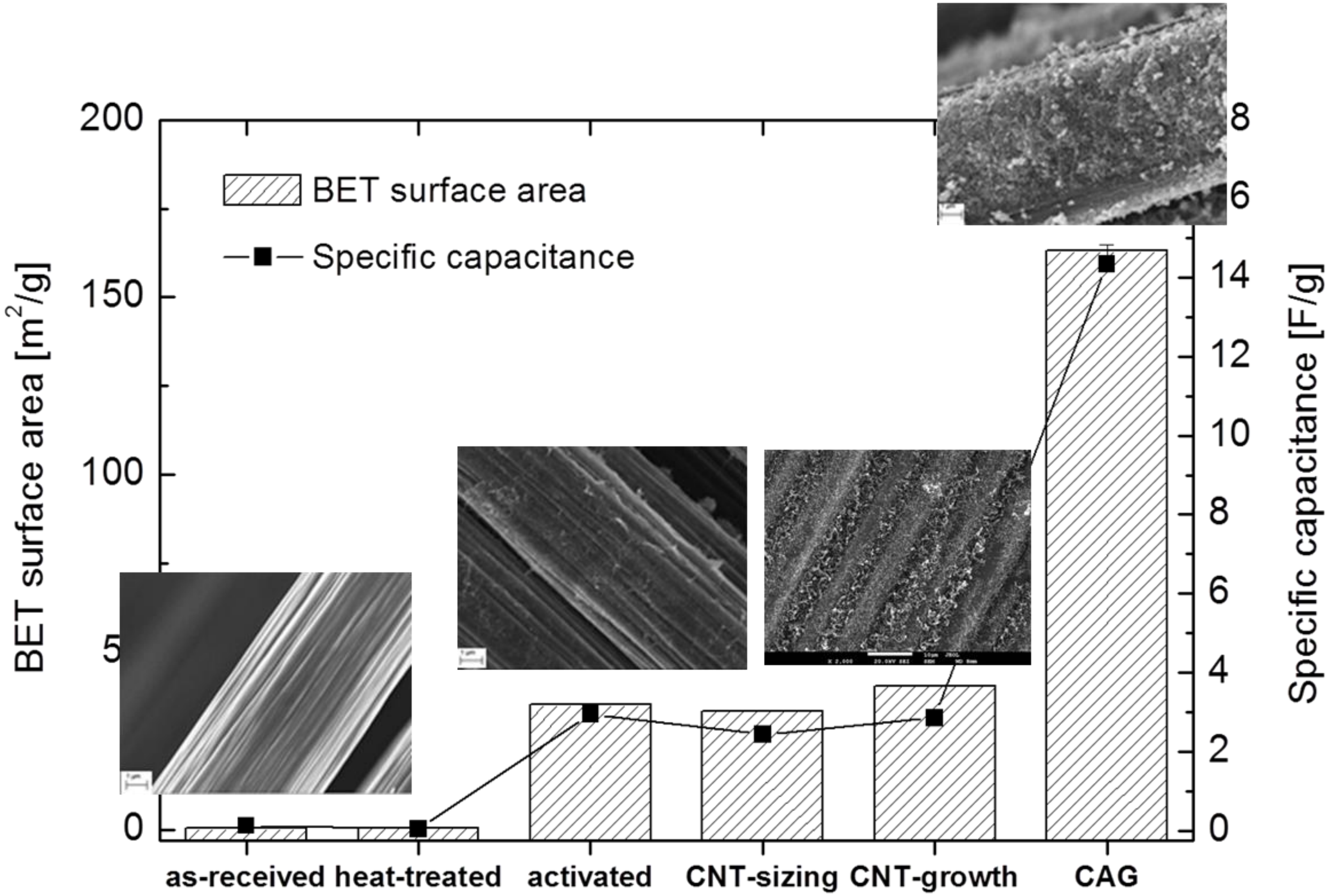
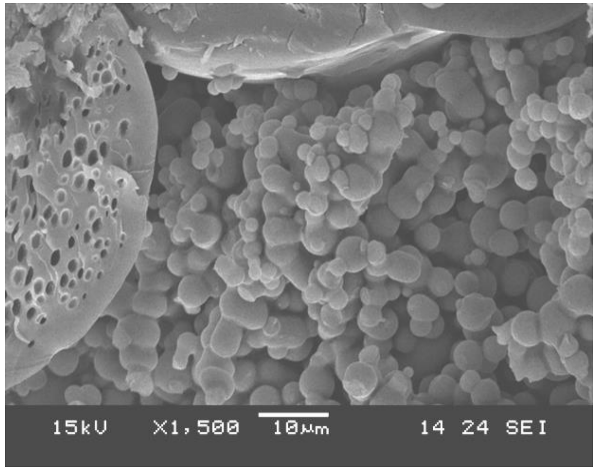
Reinforcement – Different Approaches

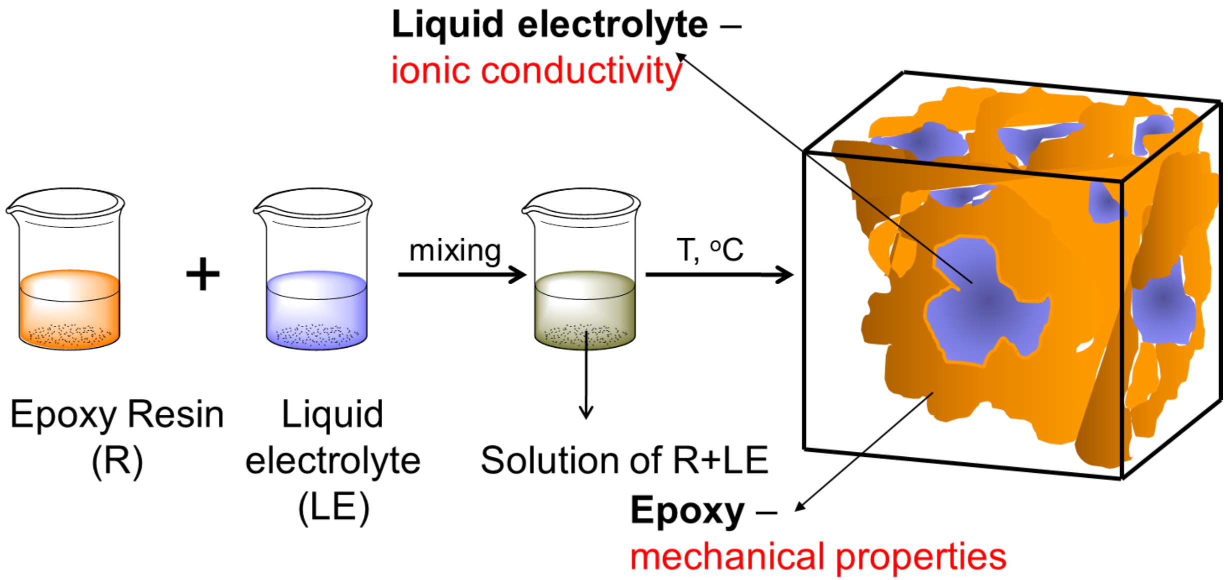


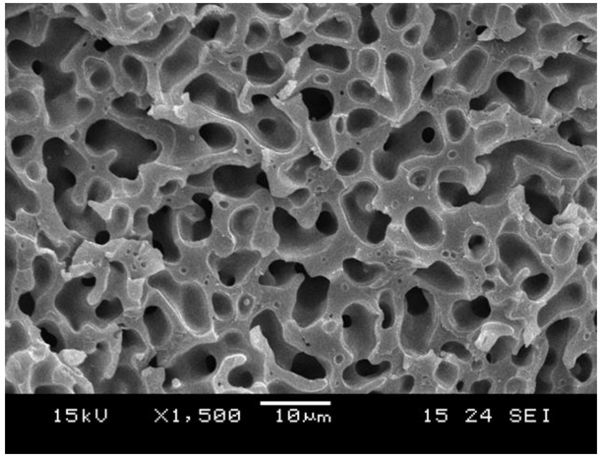
N.B. As-received CF=0.2 m²/g

Multifunctional Resin Development

- Development of nanostructured matrix materials with optimum electrolyte & mechanical properties.
- Gel polymer electrolytes
  - ⇒ *Improved durability, cheap, easy to prepare & wide voltage window.*
- Exploit two phase system that spontaneously forms a bi-continuous nanostructure;
  - ⇒ *One phase provides ionic conductivity, the other structural rigidity.*







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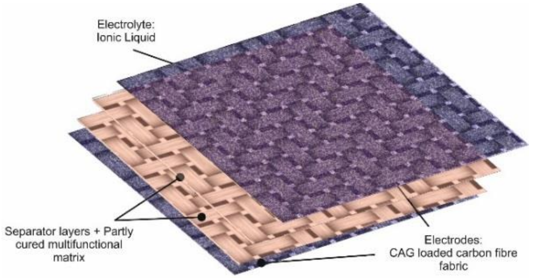
Device Evolution

1st Generation – ACF/PEGDGE

Γ=0.00001Wh/kg
P=0.14W/kg

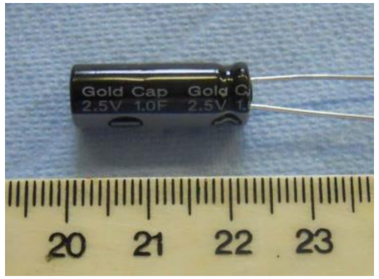
E~25GPa



2nd Generation–CF/CNT/Epoxy/IL

Γ=0.0089Wh/kg
P=0.0021W/kg

E~60GPa; G_{12}~0.5GPa



Conventional supercapacitor

Γ=2.9Wh/kg & *P*=6900W/kg

3rd Generation – CF/CAG/Epoxy/IL

Structural; Γ=0.2Wh/kg; P=18W/kg & G_{12}~0.6GPa

Semi-structural; Γ=1.0Wh/kg; P=290W/kg

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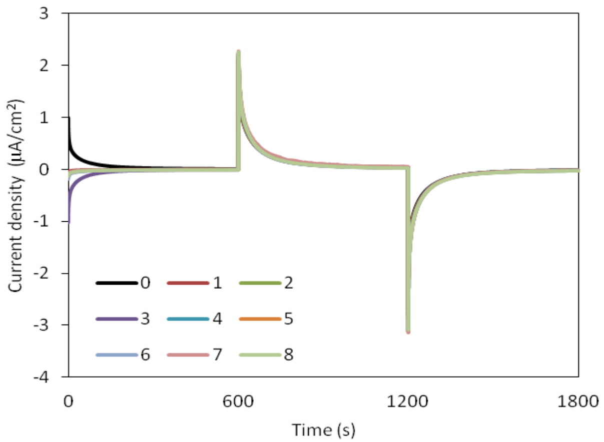
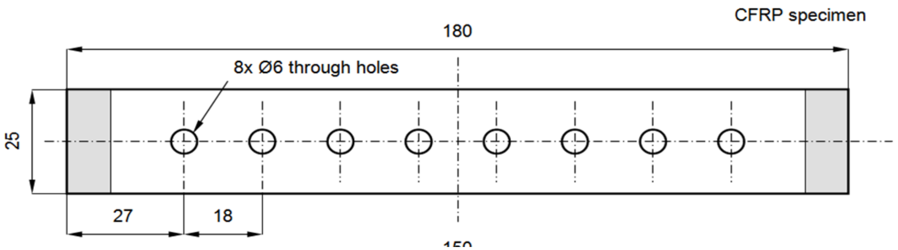
Systems (Engineering Issues)

- ⇒ how do we design with these materials?
- ⇒ how do we scale up fabrication and finish?
- ⇒ how to we connect to the electrical systems?
- ⇒ how do we connect protect these materials from the environment?
- ⇒ what is the long-term performance?
- ⇒ how do we repair/inspect/dispose?



- Aim to have a methodology in place to design, scale-up and own structural power materials.



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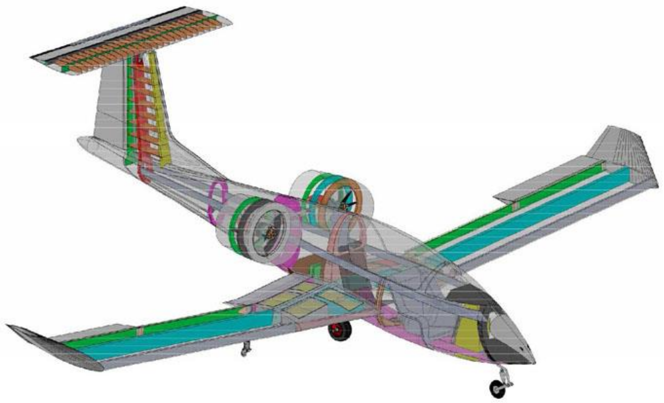
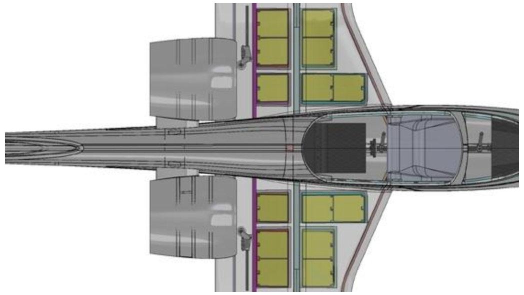
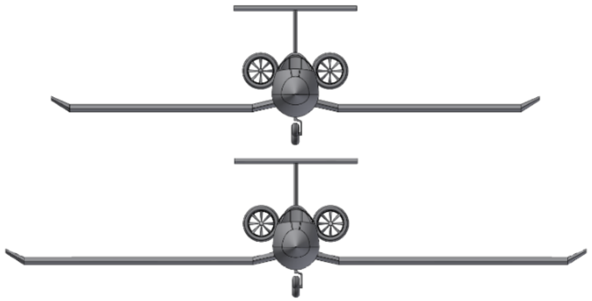
System Modelling

- Modelled Airbus E-Fan such that all the load-bearing material replaced by structural power material.
- Removed battery (167kg), and hence calculated:
  - *Required electrical performance of structural power material to achieve same range (160km).*
  - *Extended range for when maintaining the aircraft weight (500kg) – i.e. replacing battery weight with structural power material.*
- Critical observation – no fuel or batteries so wing does not need to be hollow.
  - Hence wing can be more slender/shorter, and hence reduced drag….
- N.B. calculations suggest a fully electric aircraft would require *1000Wh/kg* conventional batteries!







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Technology Demonstrator – Plenum Cover

- Design and manufacture of demonstrator components utilising multifunctional composite materials.
  - First stage (*multifunctional structure*) by embedding batteries into CFRP laminate
- Any energy storage capacity that could improve energy storage or reduce overall structural/systems weight would be valuable.

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Technology Demonstrator – Boot lid Design

13kg

5.2kg

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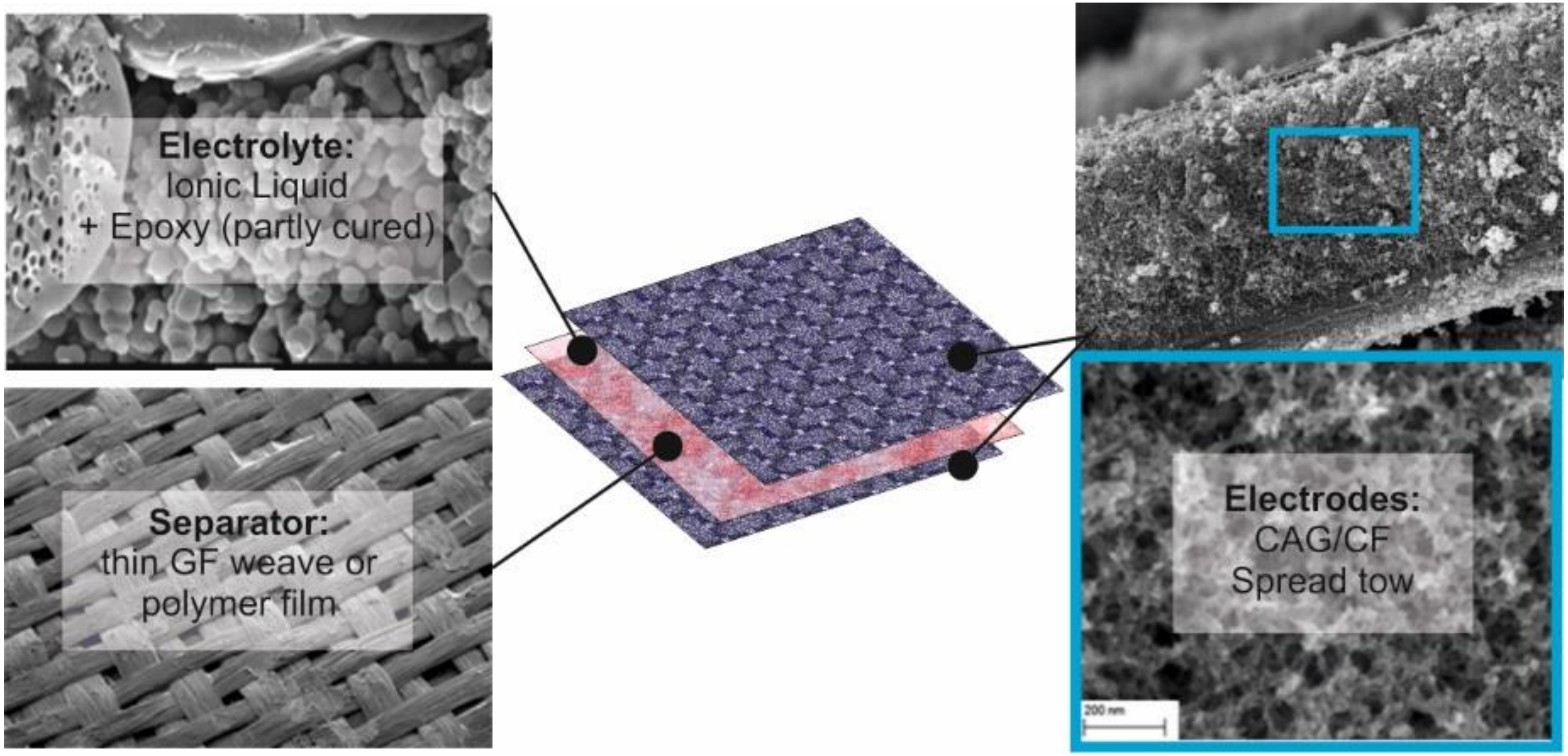
Fourth Generation Device



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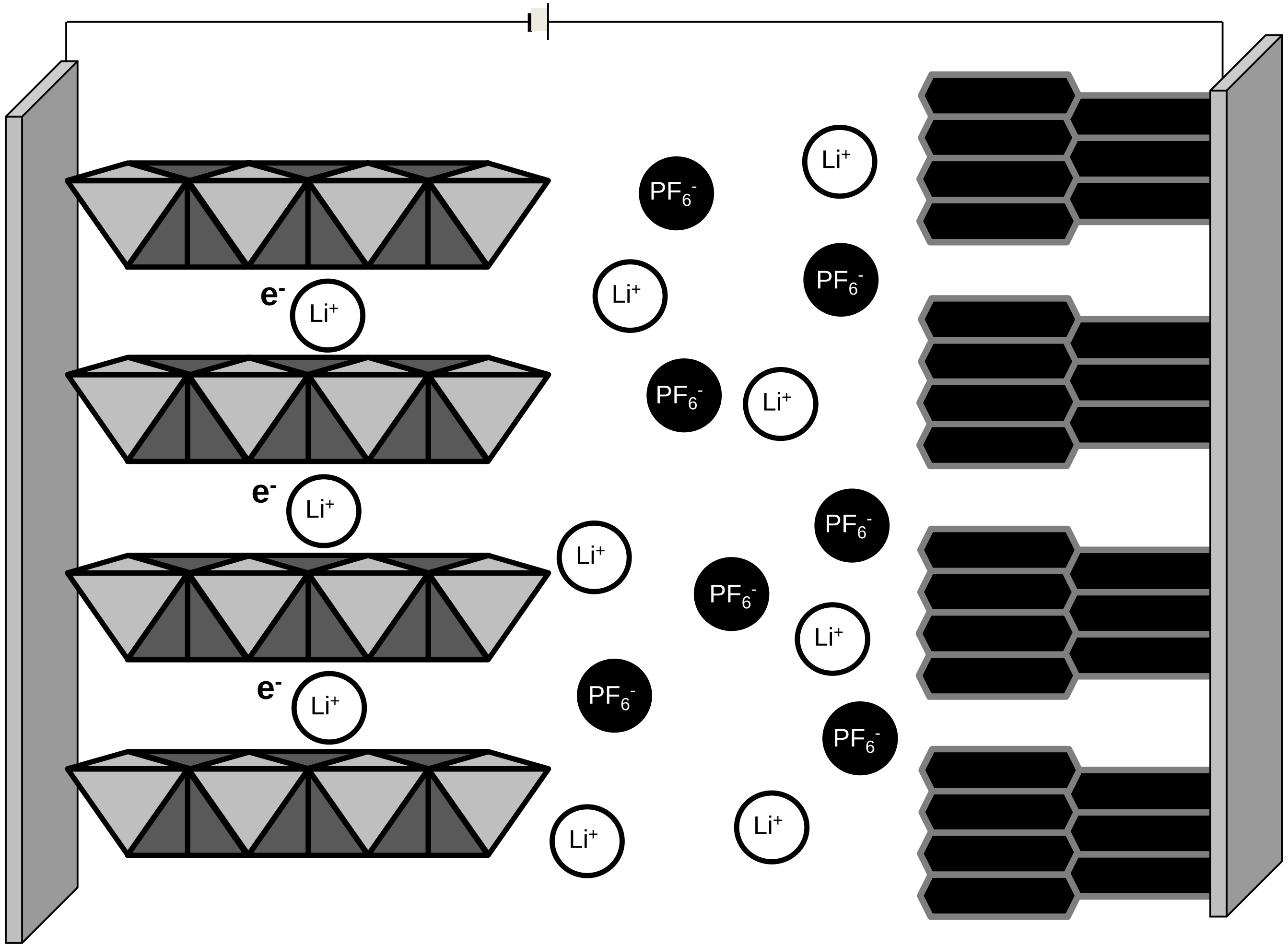
Structural Batteries

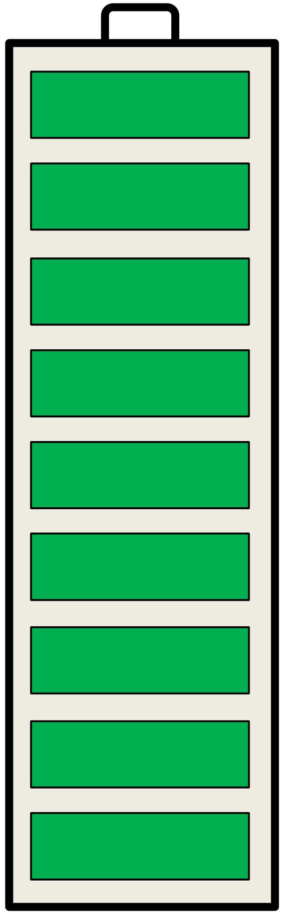
Chalmers & KTH

Challenges: The Li-ion battery



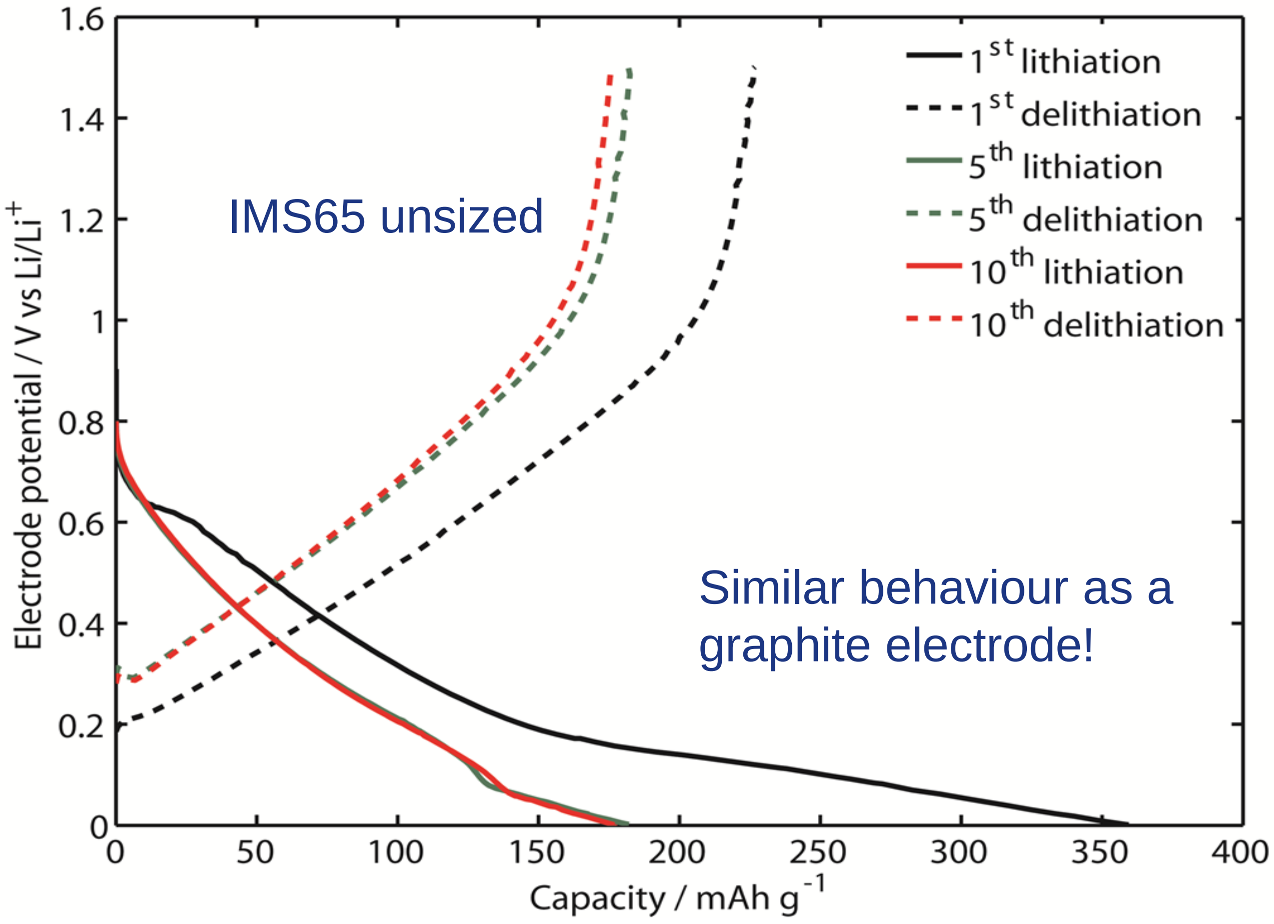
Positive electrode

Negative electrode



Leijonmarck, 2013

Capacity of PAN-based carbon fibres



Kjell et al, J Electrochem Soc., 2011

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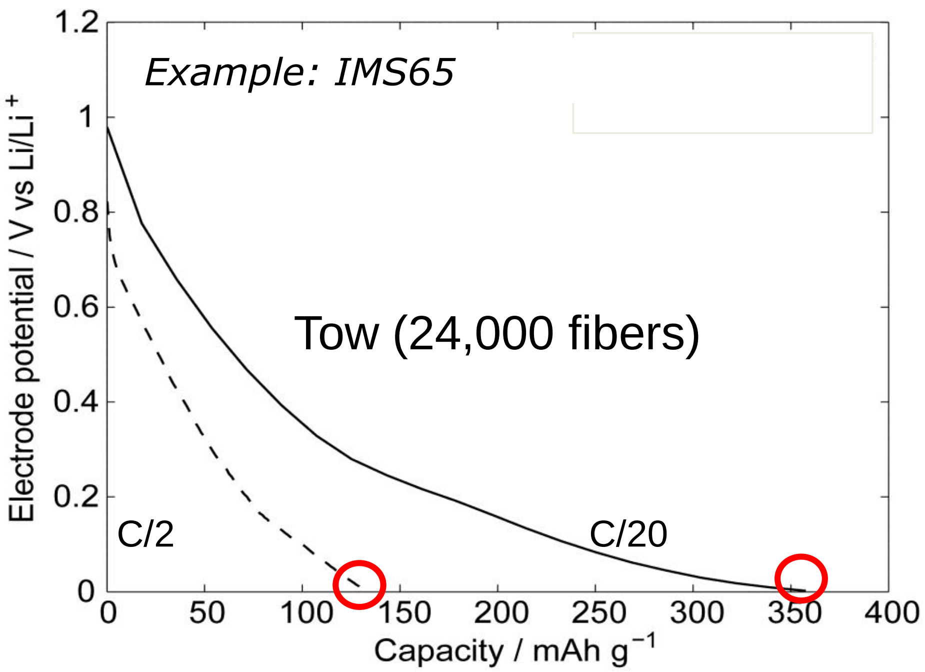
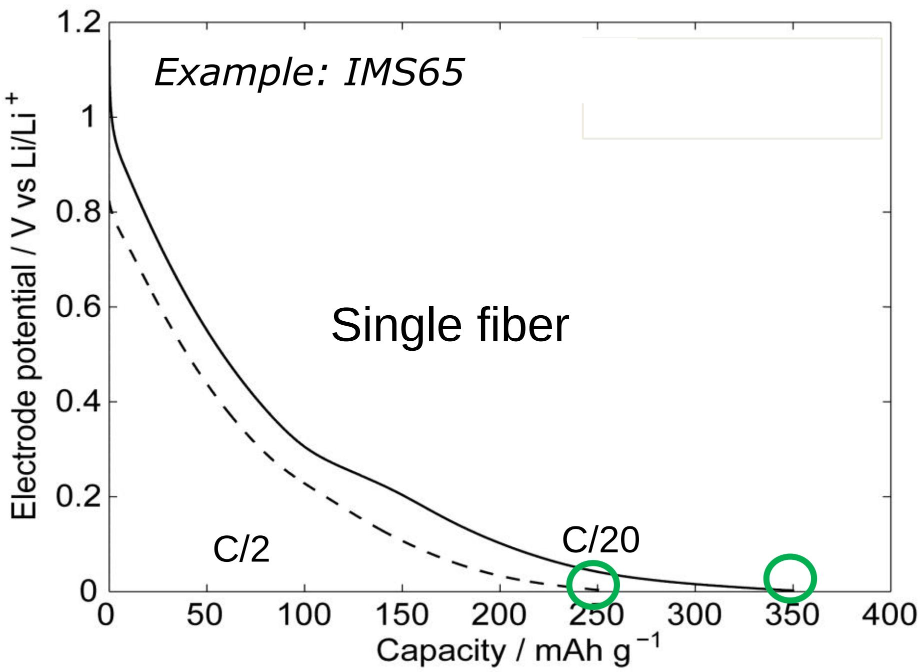
Reversible capacity of PAN-based carbon fibres

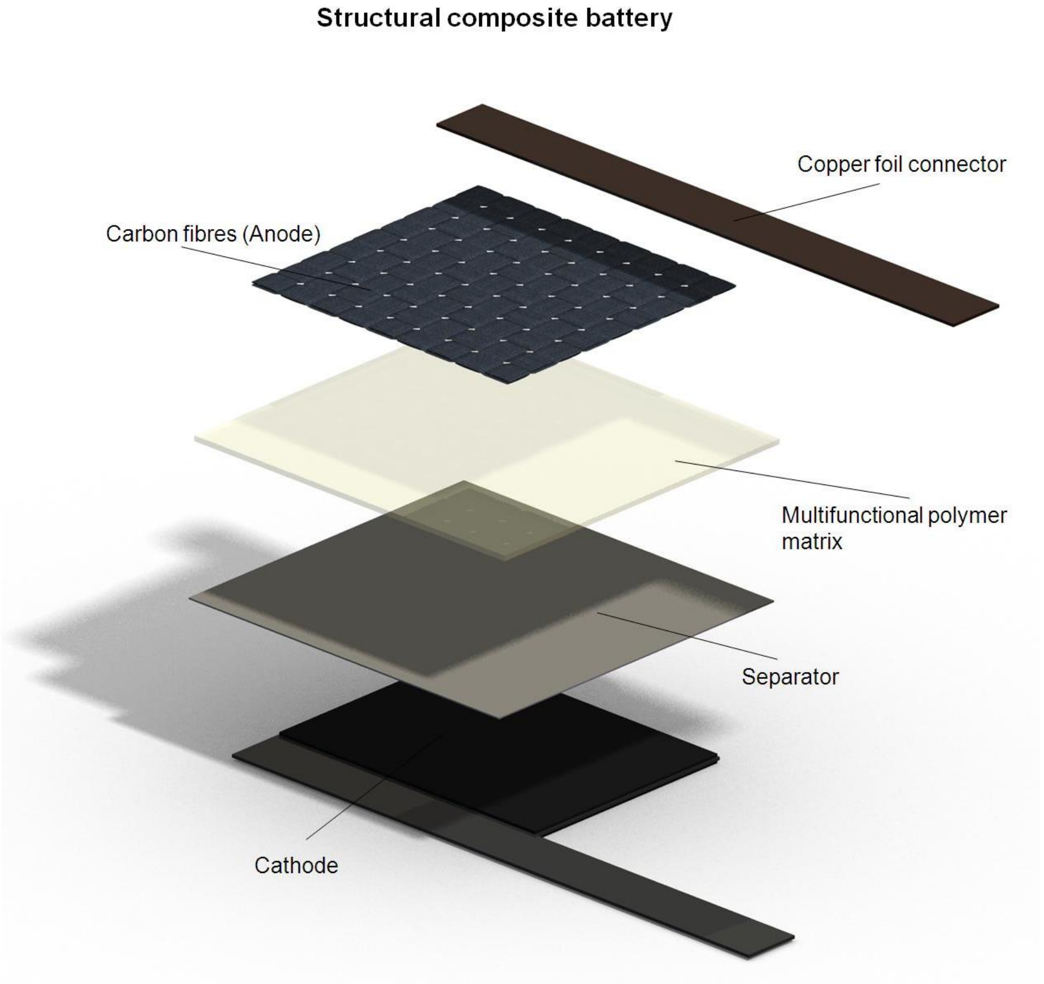


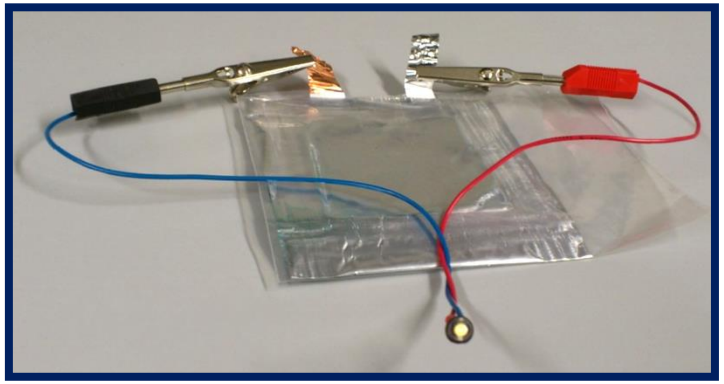
Kjell et al, J Electrochem Soc., 2011



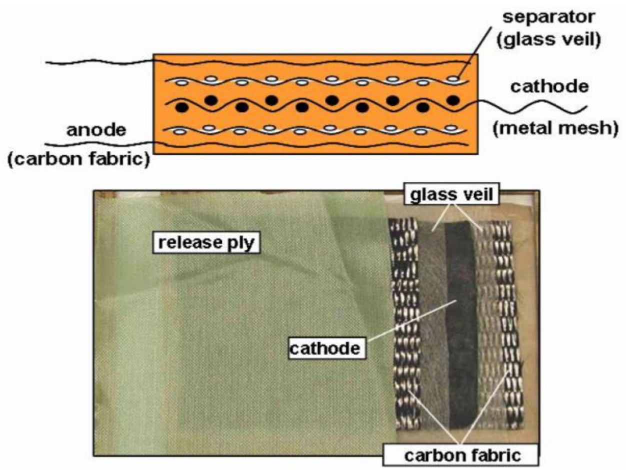
Kjell et al, J Electrochem Soc., 2013

Device architecture – Structural Battery





Structural Battery (SICOMP)



Structural Battery (ARL)

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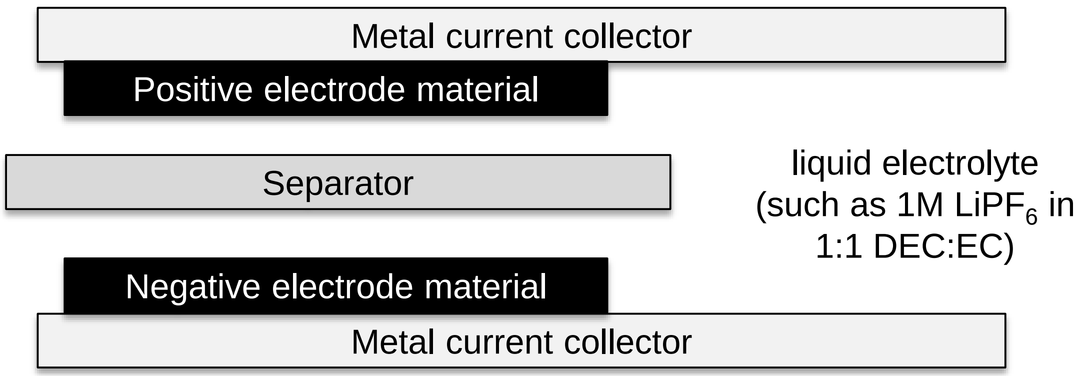
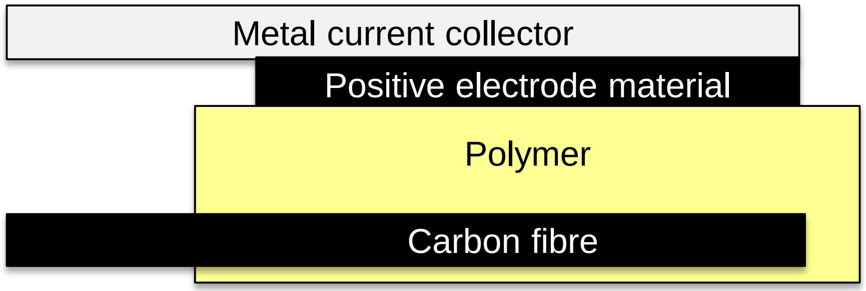
Choice of architecture

Standard battery:



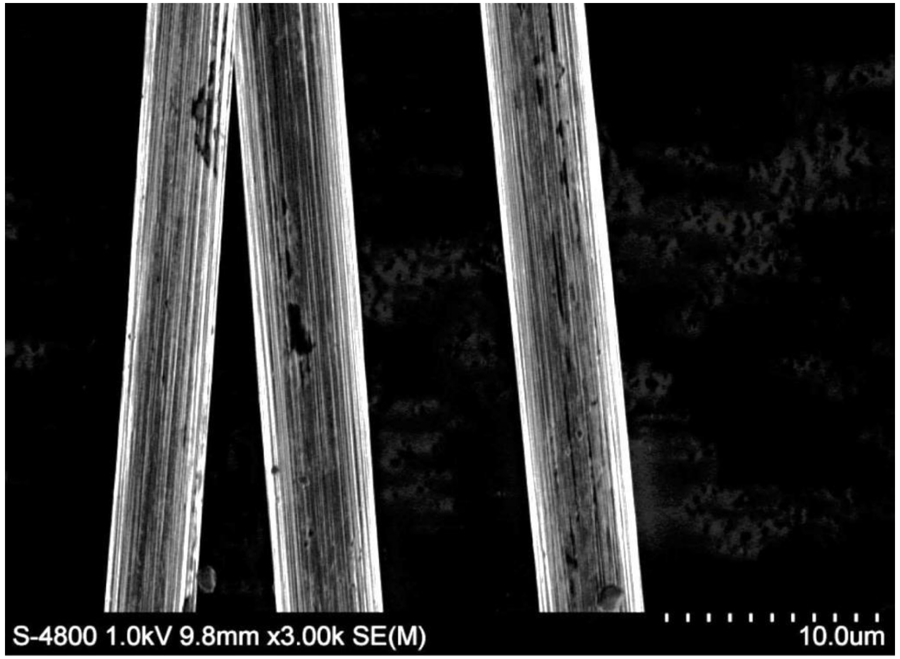
Structural battery:



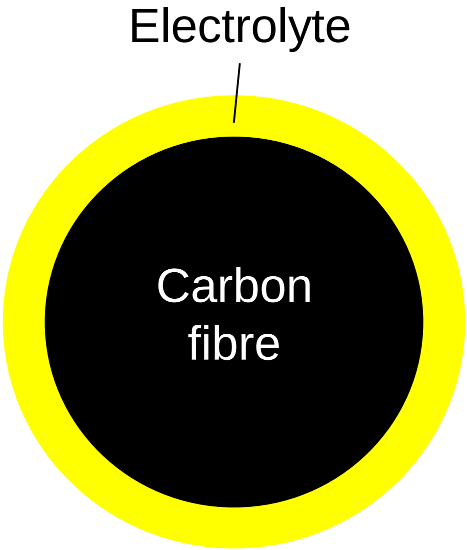
	Liquid electrolyte	Solid polymer electrolyte
Electrolyte thickness	30 µm	30 µm
Effective conductivity	0.7 mS/cm [1,2]	1.5 µS/cm [3]
Ohmic drop at 1 mA/cm^2	4 mV	2 V

[1] T.B. Reddy, Linden's Handbook of Batteries, McGraw-Hill (**2011**)
[2] P. Arora, Z.M. Zhang, *Chemical Reviews*, 104 (**2004**) 4419-4462
[3] M. Willgert, M.H. Kjell, E. Jacques, M. Behm, G. Lindbergh, M. Johansson, *European Polymer Journal*, 47 (**2011**) 2372-2378.

Geometry of the electrolyte/separator

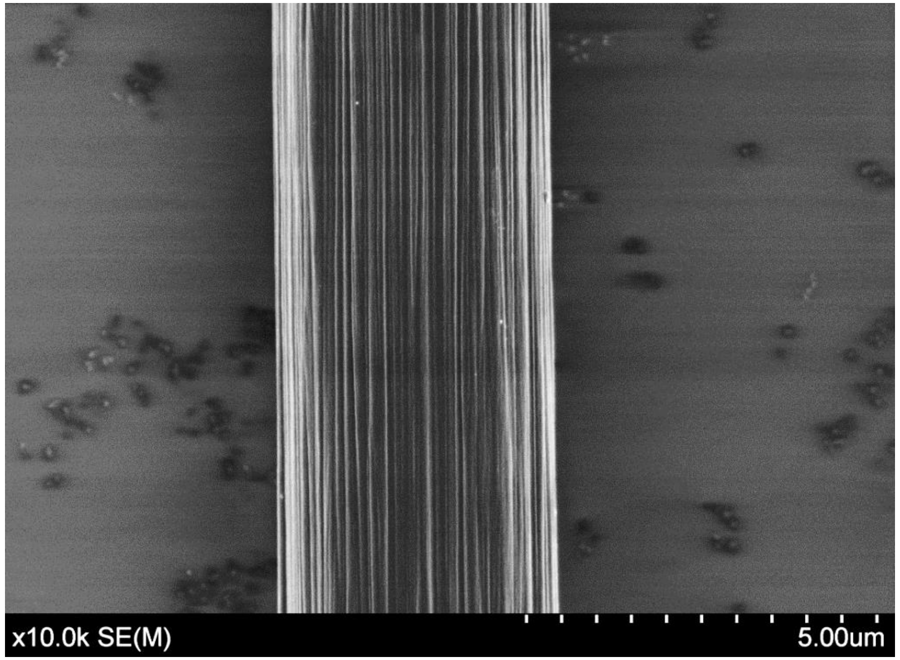


Carbon fibres

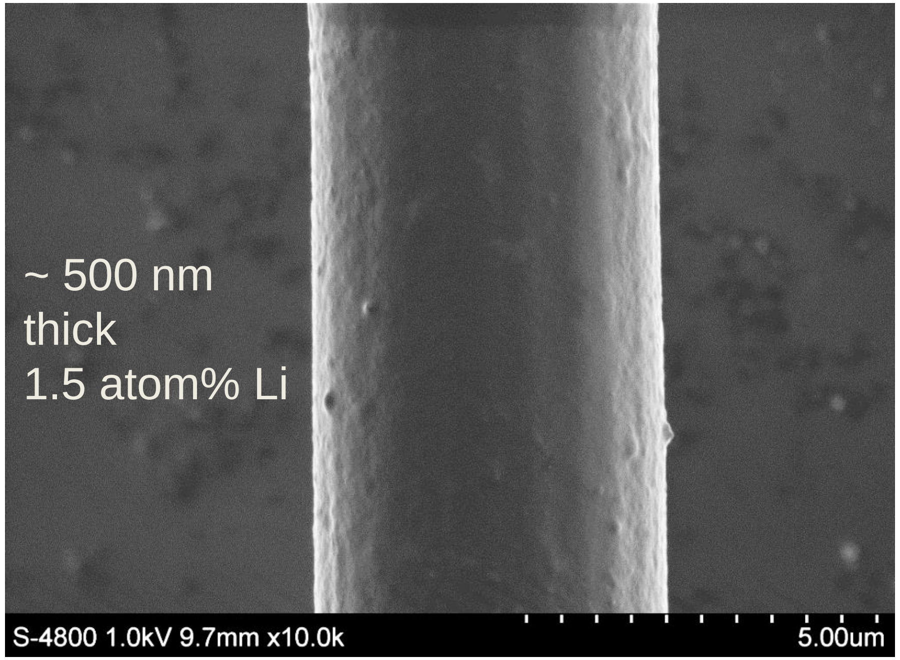


Goals:
- Thin polymeric coating
- Fully covering
- Lithium ion-containing

Electropolymerized SPE-coating



Unmodified carbon fibre



Electropolymerized carbon fibre

Leijonmarck et al., Comp Sci Technol, 2013

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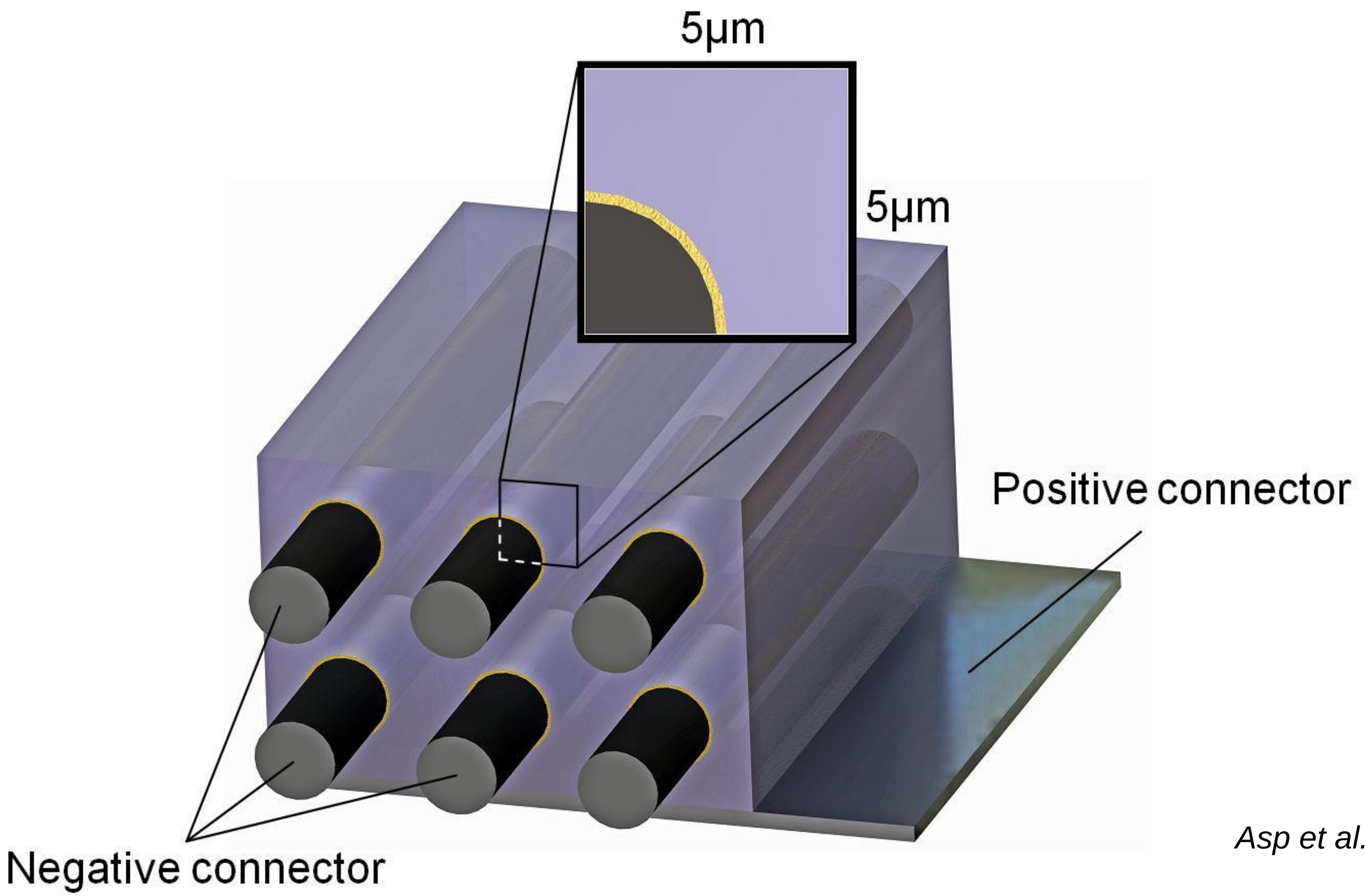
Device architecture – the coated CF battery



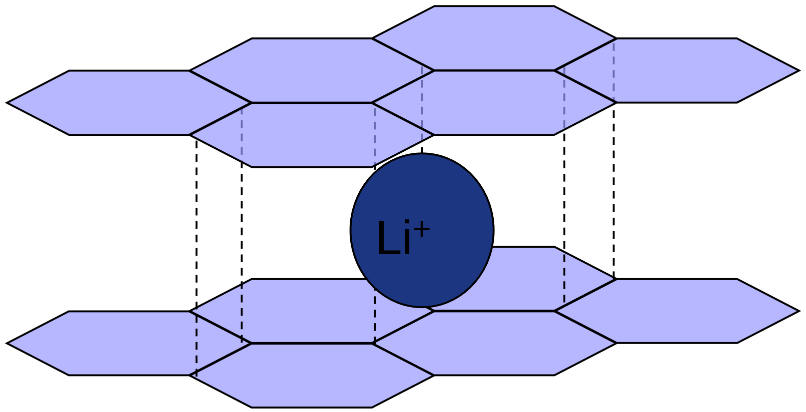
Asp et al. PCT/EP2013/068024, 2013.

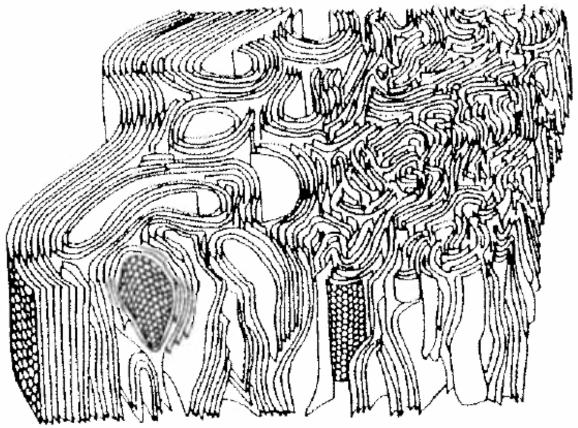
Effect of microstructure on multifunctional performance

Carbon fibres

Mechanical properties ⟷ Microstructure ⟷ Electrochemical properties

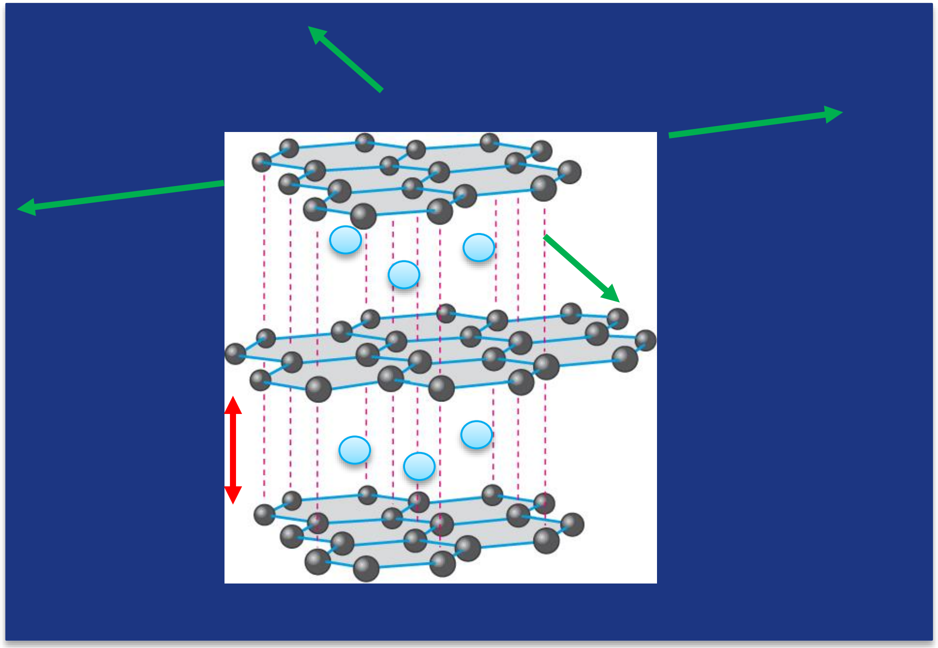
"Known"   Unknown





Fib-SEM, TEM
In-situ Raman and APT

Li-ion intercalation in graphite
(possible cause for damage)



Interlayer spacing in graphite, d002, is 3.354Å

From earlier work (Kjell et al. ECS 2011)

Longitudinal swelling of IMS65 fibres:
1% at full charge (C/10, i.e. 317 mAh/g)

Radial swelling of IMS65 estimated to:
~8% at full charge

In LiC_6 (stage 1) of crystalline graphite:
- The interlayer distance increases by **10%**
- The C-C bond distance increases by **1%**

Thinius, S. et al., J. Phys. Chem. C, 2014, 118, 2273−2280

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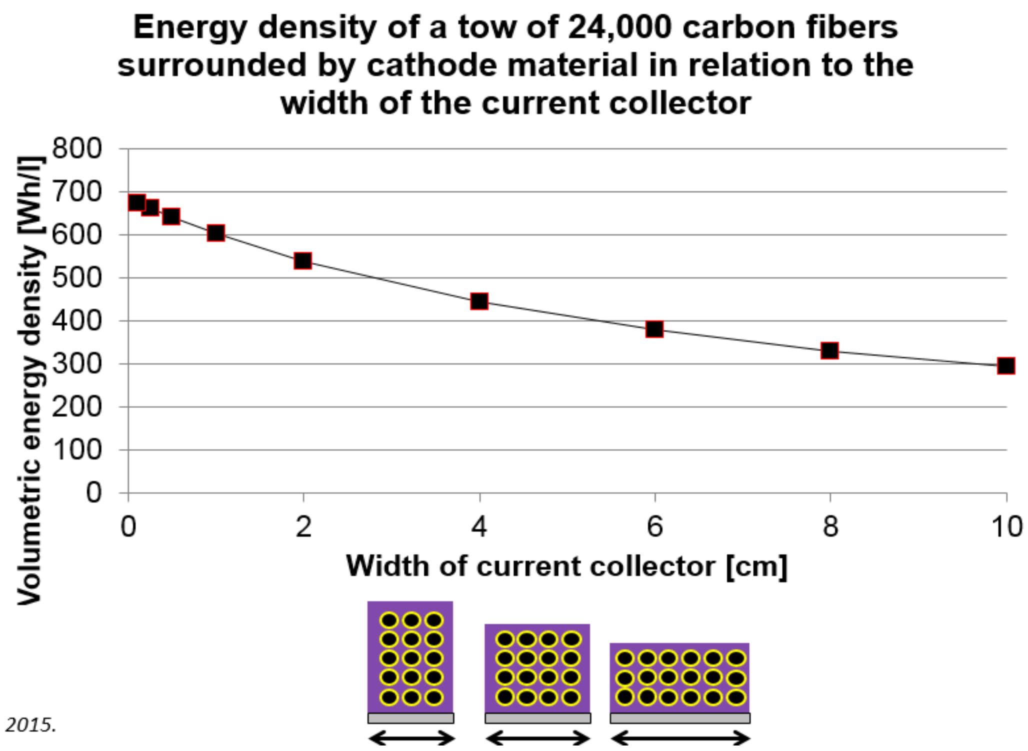
Energy density of CF battery, depending on design



Asp et al., ICCM20, 2015.

Targets: capacity 150 Wh/kg (medium-term), 250 Wh/kg (long-term)
rate capability 100 Wh/kg (medium-term)
ply shear modulus 1 GPa (medium-term)
cycle life 75% of initial capacity after 1000 cycles (long-term)

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Damage Tolerance & Durability of Structural Power Composites Project

Objectives of Research Project (Autumn 2017)

- ***Objective 1 (KTH)*** – Perform mechanical tests in conjunction with fractographic analysis and, with reference to the damage mechanisms in conventional composites, characterize detailed processes by which these materials damage and fail (Task 1).

- ***Objective 2 (Chalmers)*** - Investigate the influence of charge state and charge/discharge cycling on damage processes during impact (*supercapacitors - ICL*) and mechanical degradation (*batteries – Chalmers/KTH*) (Task 2).

- ***Objective 3 (ICL)*** - Investigate strategies to enhance mechanical properties of structural power materials and formulate strategies to promote benign behaviour during rapid discharge without compromising electrical performance (Task 3).

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Task 1 - Damage Processes in Structural Power Materials (KTH Lead)

- High fidelity mechanical tests developed to characterize properties from the single fibre level up to laminate or 3D-battery device level.
- New tests developed for lamina scale properties, drawing on those applied in conventional composites research.
- Culminate in assembly and mechanical characterisation of full cells (batteries and supercapacitors), focusing on critical mechanical properties.
- Detailed fractography to deduce the influence of the electrodes, electrolyte and architecture on the damage processes.
- For supercapacitors, the research will characterise the damage processes during impact and the resulting residual strength.

Task 2 - Electrical/Mechanical Interactions in Structural Power Materials (Chalmers Lead)

- *Structural Supercapacitors* - nail gun penetration and low velocity impact tests to investigate the electrical and mechanical behaviour of charged devices.
- The influence of the degree of charge on the subsequent failure and localised rapid discharge processes will be investigated.
- *Structural Batteries* – focus will be on the influence of charge/discharge cycling on the mechanical degradation (i.e. durability) of the devices.
- Analysis will be performed on samples that have been electrochemically cycled to investigate physical and mechanical degradation effects.
- Some mechanical testing performed simultaneously whilst electrochemical cycling.

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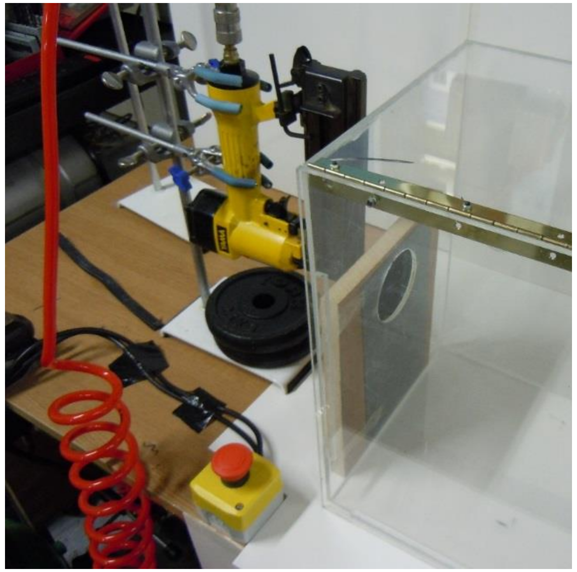
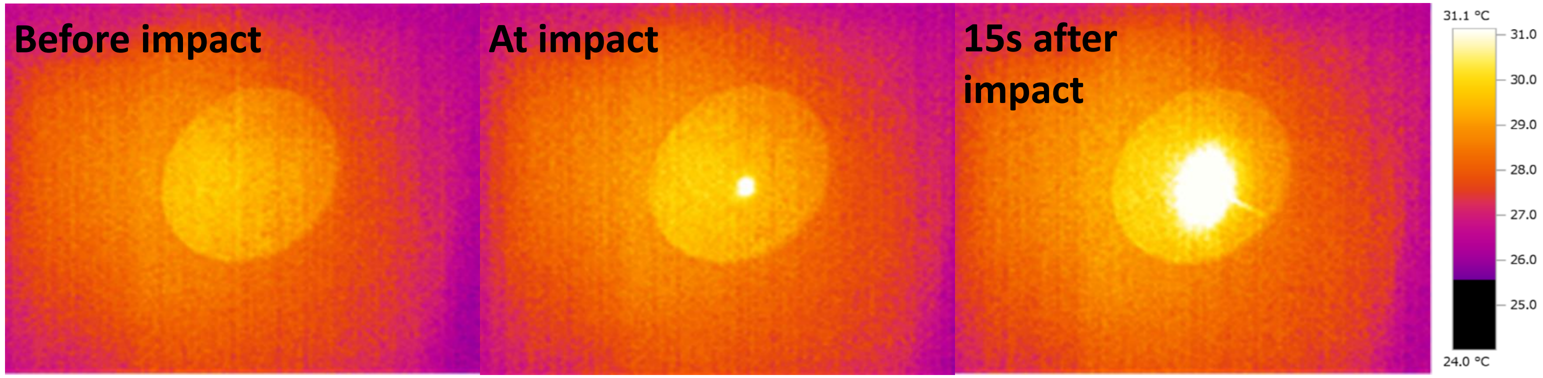
Task 2 - Electrical/Mechanical Interactions - example

⇒ Nailgun penetration of charged laminates.

⇒ Simplistic demonstration of crashworthiness capabilities of early devices, showing local heating of the penetration site, but no catastrophic issues.

⇒ This aspect will be investigated, to glean a deeper insight into the damage processes (both mechanical and electrical) during penetrative impact of charged devices





Thermal camera images of penetrated face

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Task 3 Enhanced Damage Tolerance and Durability of Structural Power Materials (Imperial Lead)

- Based on results of prior Tasks, pursue modification of the device designs for enhanced damage tolerance, durability and electrical safety.
- *Structural Supercapacitors* - methods to enhance interlaminar toughness via through-thickness reinforcement and hybridisation of the carbon aerogel.
- Such configurations will also be investigated as a means to introduce materials that could mitigate rapid heating of the device during penetration induced discharge.
- *Structural Batteries* - strategies to mitigate the stresses and damage induced by dimensional changes during charging/discharging will be addressed by surface modification of the electrodes as well as adaptation of the matrix chemical structure towards specific electrode surfaces.
- Alternatively, laminated batteries assembled from many thin layers (like an ordinary composite laminate) using appropriate lay-up tailoring to reduce unwanted high intra- and interlaminar strains, will be investigated.

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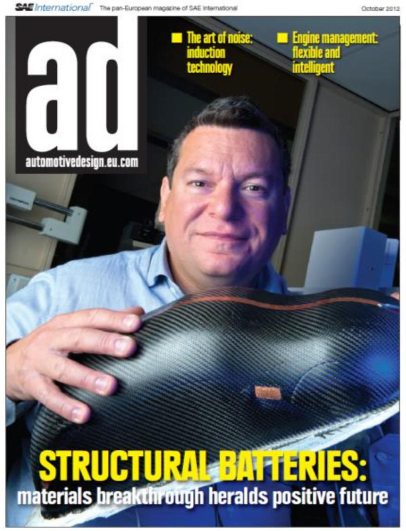
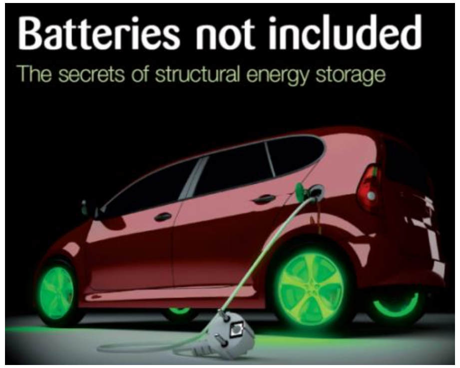
Gantt from Research Project

					Year 1												Year 2												Year 3											
Task	Details	ICL	Chalmers	KTH	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
0	**Project Management**															D1												D2												D1
1	**Damage Processes in Structural Power Materials**																																							
1_1	*Supercapacitor Architecture Design*																																							
1_2	*Supercapacitor Fabrication Studies*																																							
1_3	*Battery Architecture Design*																																							
1_4	*Battery Fabrication Studies*																																							
1_5	*Micromechanical Characterisation*																																							
1_6	*Laminate Characterisation*																																							
1_7	*Engineering Characterisation*																																							
2	**Electrical/Mechanical Interactions in Structural Power Materials**																																							
2_1	*Rapid Discharge Protocol Formulation and Design*																																							
2_2	*Impact and Penetration Testing*																																							
2_3	*Post-Failure Characterisation*																																							
2_4	*Mechanical degradation of batteries*																																							
2_5	*Li-intercalation vs fibre microstructure*																																							
2_6	*Combined mechanical/electrochemical cycling*																																							
3	**Enhanced Damage Tolerance & Durability of Structural Power Materials**																																							
3_1	*Damage Tolerance Enhancement - Supercapacitors*																																							
3_2	*Damage Tolerance Enhancement - Batteries*																																							
3_3	*Rapid Discharge Ameloration - Supercapacitors*																																							
3_4	*Durability Enhancement - Batteries*																																							

Extra Slides



Automotive Design



IOM3
Materials World

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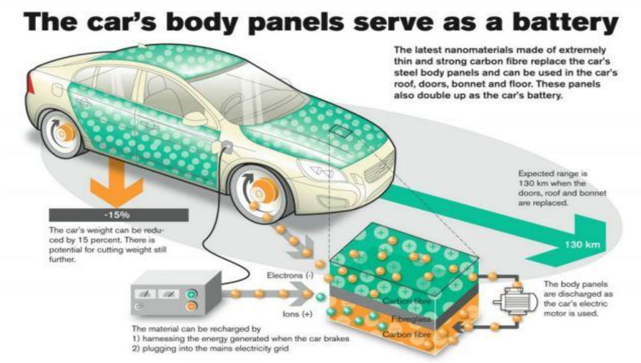

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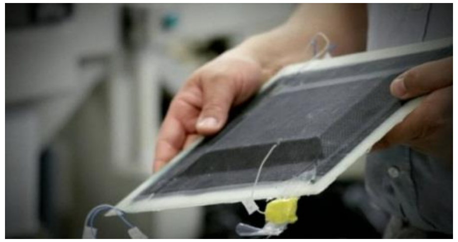

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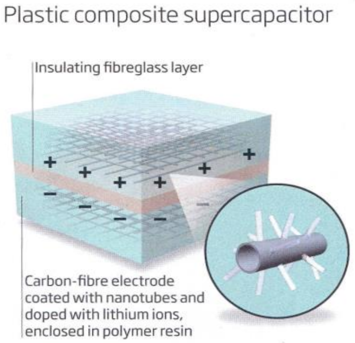

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