Multifunctional Structural Power Composites – Challenges and Future Opportunities

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Introduction and Motivation
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.

• Synergy of lamination; common to both electrochemical devices and structural composites
**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

**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


Supercapacitor Device

Conventional Supercapacitor

Structural Supercapacitor

Electrolyte: Nanostructured interpenetrating structural matrix/ionic liquid

Nanoporous membrane

Electrodes: Carbon aerogel/spread low carbon fibres
Constituent Development and Composite Performance
Reinforcement Development

Raw T300 fibre

- Resorcinol-formaldehyde gel pyrolysis
- KOH heat-treatment
- In-situ growth of carbon nanotubes

- Aquacetyl solution sizing

- CAG-coated fibre
- KOH activated fibre
- CNT-sized fibre
- CNT-grown fibre
Reinforcement – Different Approaches

N.B. As-received CF=0.2 m²/g
Multifunctional Resin Development

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

![Diagram of multifunctional resin development](image)

- Epoxy Resin (R) + Liquid Electrolyte (LE) → Solution of R+LE
- Ionic conductivity 0.43 mS/cm, Young's Modulus 0.23 GPa
- Ionic conductivity 0.15 mS/cm, Young's Modulus 0.90 GPa
Device Evolution

1st Generation – ACF/PEGDGE
\( \Gamma = 0.00001 \text{Wh/kg} \)
\( P = 0.14 \text{W/kg} \)
\( E \approx 25 \text{GPa} \)

2nd Generation – CF/CNT/Epoxy/IL
\( \Gamma = 0.0089 \text{Wh/kg} \)
\( P = 0.0021 \text{W/kg} \)
\( E \approx 60 \text{GPa}; G_{12} \approx 0.5 \text{GPa} \)

Conventional supercapacitor
\( \Gamma = 2.9 \text{Wh/kg} \) & \( P = 6900 \text{W/kg} \)

3rd Generation – CF/CAG/Epoxy/IL

Structural; \( \Gamma = 0.2 \text{Wh/kg}; P = 18 \text{W/kg} \) & \( G_{12} \approx 0.6 \text{GPa} \)

Semi-structural; \( \Gamma = 1.0 \text{Wh/kg}; P = 290 \text{W/kg} \)
Demonstrators
Technology Demonstrators

• Evaluation and assessment of benchtest components utilising multifunctional composite materials

  ⇒ *Demonstration of multifunctional structures (Plenum cover) on Volvo S80 to explore the manufacturing and systems issues.*

  ⇒ *Small scale demonstration of structural supercapacitors using a RC car.*

  ⇒ *Full scale boot lid incorporating 16 structural supercapacitor cells.*
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.

![6.2kg](image1)

![2.5kg](image2)
Technology Demonstrator – Boot lid Design

13kg

5.2kg
Technology Demonstrator – Boot-lid
Challenges

• Current performance - c.f. conventional supercapacitor (2.9Wh/kg & 6900W/kg)
  ⇒ 1Wh/kg & 290W/kg (semi-structural);
  ⇒ 0.2Wh/kg & 41W/kg (structural).

• Fundamental understanding of design and optimisation of interfaces (fibre/matrix and electrode/separator) for improved multifunctional performance.
  ⇒ Underpinning science needed to move field forward.

• Mechanical properties – still poor, particularly interface/matrix dominated.
  ⇒ Intermediate focus on stiffness dominated regime (i.e. Semi-structural).

• Engineering and fabrication challenges to be resolved.
  ⇒ Innovation needed to apply ‘moisture-free battery fabrication’ techniques to large scale composite production.

• Strategies to improve –
  ⇒ Power density – improve ionic conductivity and reduce separator distances.
  ⇒ Energy density – utilise hybrid/asymmetric devices.
  ⇒ Mechanical properties – microstructures with different lengthscales.
Future Opportunities

- **ICL/Chalmers/KTH – unrivalled level of experience in structural power**
- **Going beyond Smart Structures**
  - New interdisciplinary field of multifunctional materials;
  - Fertile ground for development of new technologies;
  - Novel material architectures - stimulating development of monofunctional electrical & mechanical materials;
  - Solutions for conventional composites - electrical conductivity (lightning strike).
- **Alternative electrochemistries**
  - Pseudocapacitance & hybrid/asymmetric devices;
  - Structural batteries highly promising (2x energy density of SOTA devices);
  - Added functionalities identified – sensing, actuation, energy harvesting.
- **Highly diverse range of potential applications**
  - Mainly transportation and aerospace driven to date;
  - As performance improves, sparked interest from other sectors (e.g. mobile electronics).
Batteries not included
The secrets of structural energy storage

The car’s body panels serve as a battery

IOM3
Materials World

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www.energyopportunities.tv/Editorial-Features/An-
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Plastic composite supercapacitor

New Scientist